Development lengths of high-strength self-consolidating concrete beams

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Editor's quick points

- Because of the increased use of self-consolidating concrete (SCC), it is important to understand the bond behavior of prestressed strands in SCC.
- This paper presents an experimental determination of development lengths of prestressed strands in SCC beams and compares those lengths with the development lengths of strands in conventionally cast concrete.
- The experimentally determined development lengths are compared with calculated development lengths using American Concrete Institute/American Association of State Highway and Transportation Officials and National Cooperative Highway Research Program equations. Application of either equation yields conservative development lengths.

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. The self-weight of the SCC combined with its high deformability without segregation allow for compaction without vibration.[1,2]

SCC was developed to reduce the amount of labor required for placement and finishing of concrete. Its high deformability allows it to be placed through congested reinforcement without the skilled workers necessary for vibratory consolidation.[2,3] Therefore, SCC has been used extensively in architectural projects and has the potential for use in highly congested members with narrow cross sections, such as prestressed concrete bridge girders.

This research program measured the development lengths in SCC beams and compared them with those determined from conventional, high-strength concrete beams. The primary objectives were to determine the following:

- the effect of SCC on development lengths in prestressed concrete beams
- whether the American Concrete Institute's *Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary (ACI 318R-08)*[4] and American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[5] equations used to estimate development length are applicable to SCC beams

- what modifications might be needed to these equations

Background

Numerous research programs concerning the bond characteristics of prestressing strand in prestressed concrete members have been conducted beginning with Janney's work in the 1950s.[6] Much of this previous research used conventional concrete, but this background section discusses some of the recent research on transfer and development length in SCC members.

Hamilton et al.[3] conducted structural tests on six AASHTO Type II girders. Three girders were cast with SCC and three with a conventional concrete. Two of the girders from each mixture were outfitted with a composite section to simulate the action of a bridge deck. The remaining girders were tested without the composite section.

Structural tests were performed using a simply supported beam arrangement. A single point load was placed at a specified embedment length from the end of the beam being tested. The span length was such that both ends of the beams could be used for testing. Two girders were tested for shear behavior, two girders for combined shear and flexure, and two girders for strand-slip failure. All of these failure modes were used to compare the behavior of SCC girders with that of conventional concrete girders. No significant differences were noted in flexural capacity, shear capacity, or web cracking between the SCC and conventional concrete girders. It was noted that for strand-slip failures, abrupt prestressing force transfer may have contributed more to girder failure than concrete type.[3]

Burgueno and Haq[7] evaluated the transfer and development lengths of 0.5-in.-diameter (13 mm), 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 mixture proportions had a design compressive strength of 7000 psi (50 MPa) and entrained air content of 6%.

Transfer length was determined using both measured strand slip and concrete strain at the level of the prestressing steel. Two tests for development length were conducted on each beam specimen for a total of four tests for each mixture. An iterative approach was used to determine flexural bond length by bounding the flexural and bond-slip failure modes. Transfer lengths for the SCC beams were determined to be within the limits of the equation provided by ACI and AASHTO. However, SCC beams had lower bond strengths and longer transfer lengths than conventional concrete beams. SCC beams with a moderate water-cement ratio *w/c* containing modest amounts of admixtures performed closer to conventional concrete than those containing larger amounts of fines or coarse aggregate. Development-length tests were not completed at the time that the paper was published.[7]

Hegger et al.[8] examined the bond strength and shear capacity of SCC members. Tests for transfer length were conducted using 6.6-ft-long (2.0 m) rectangular test specimens containing 0.5-in.-diameter (13 mm), seven-wire prestressing strands. A prestress of 185 ksi (1280 MPa) was used, and strain was calculated using demountable mechanical (DEMEC) strain-gauge points on the concrete surface. Prestress was released gradually. Prestress transfer length was longer in SCC members because of reduced bond strength. However, the current calculations for transfer length were valid for the SCC members because they contain adequate safety margins.[6]

Larson et al.[9] studied the material and bond characteristics of prestressed concrete bridge girders made with SCC for the Kansas Department of Transportation. Initial large block pullout tests for SCC specimens with 0.5-in.-diameter (12.7 mm) strand indicated that SCC specimens had smaller first-slip and ultimate-load values than conventional concrete specimens. These large block pullout tests indicated poorer bond strengths in the SCC specimens. Development-length tests were performed as a result.

Eleven specimens containing a single strand were tested for development length. Two embedment lengths were evaluated and two cross sections were used in these tests. The first was an 8 in. × 12 in. (200 mm × 300 mm) cross section with the strand at a depth of 10 in. (250 mm), and the second was an 8 in. × 24 in. (200 mm × 610 mm) cross section with strand located 22 in. (560 mm) from the bottom.

The larger beams were used to simulate the situation where there is more than 12 in. (300 mm) of concrete below the reinforcement. These beams also were reduced to a total depth of 12 in. at midspan so that results could be compatible. Neither of these two sections contained shear reinforcement.

Multiple-strand T-beams were also cast for evaluation of the development length of multiple strands with close spacing. These beams had five bottom strands at a depth of 19 in. (480 mm), a total height of 21 in. (530 mm), and a compression flange with a width of 36 in. (910 mm). Shear reinforcement consisted of 0.5-in.-diameter (13 mm) stirrups at 6 in. (150 mm) on center. Larson et al.[9] concluded that the current equations for development length were adequate for this SCC and these beam geometries. All beams failed in strand rupture at both the 100% and 80% values of development length. Measured transfer lengths were within the AASHTO and ACI requirements as well.

Girgis and Tuan[10] investigated the bond strength of SCC using Moustafa pullout tests on 0.6-in.-diameter (15 mm)

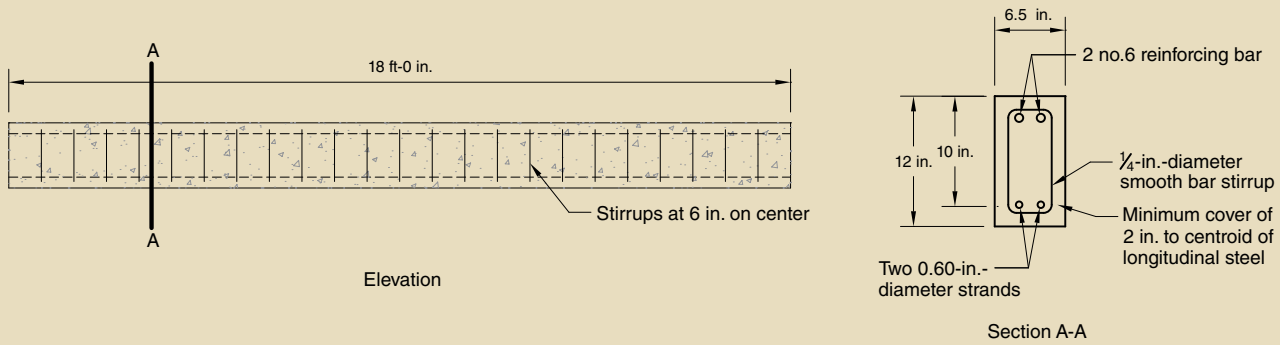

Figure 1. This drawing shows the properties of the specimens used to determine transfer and development length. Note: 1 in. = 25.4 mm; 1 ft = 0.35 m; no. 6 = 19M.

prestressing strands. In addition to the pullout tests, three concrete bridge girders were cast using two SCC mixtures and a conventional concrete mixture. Transfer lengths were determined for each of these girders by measuring concrete surface strains at the level of the steel using DEMEC points.

It was concluded from this study that bond strength for deformed bars with SCC is adequate. However, viscosity-modifying admixtures 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% longer for members cast with SCC.

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 greater bond strength at 28 days than conventional concrete had, so shorter development lengths may be possible for SCC. It was also shown through all pullout tests that smaller bar diameters had greater bond strengths.

Much research has been done on the bond characteristics of prestressed concrete members since Jack R. Janney completed his first research in the 1950s. This research has shown the same general themes in the nature of bond in prestressed concrete members. However, there has been some disagreement about whether the equations used to calculate transfer and development length in prestressed concrete members are valid. It has generally been shown that these equations are somewhat conservative and are, therefore, adequate in most cases.

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

Table 1. Mixture proportions

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*	8–9*
ADVA 555, fl oz/cwt	0	0–3*	0
VMAR-3, fl oz/yd^3	0	0–30.4*	0–30.4*

*Dosages of admixtures varied due to variations in ambient air temperatures during time of batching for individual mixtures.
Note: 1 yd^3 = 0.765 m^3; 1 lb = 0.454 kg; 1 cwt = hundred weight = 100 lb; 1 fl oz = 29.57 ml.

Table 2. NASP results for 0.010 in. of end slip

Specimen number	Strand reel 1	Strand reel 2
	Load, lb	Load, lb
1	15,010	12,930
2	16,000	12,360
3	15,050	16,030
4	13,970	15,900
5	12,930	14,140
6	n.d.*	15,560
Average	14,590	14,270
Standard deviation	1170	1670

*Only five specimens could be made using the remaining strand from strand reel 1.
Note: n.d. = no data; NSPA = North American Strand Producers. 1 lb = 4.448 N.

as well as adequacy of the code equations for transfer and development length when using 0.5 in. (13 mm) prestressing strands.[7,8,9] Research using 0.6 in. (15 mm) strands was not as conclusive.[10] This research program was intended to further investigate and answer some of the questions concerning development-length behavior of 0.6 in. strands in SCC members.

Experimental program

The research program consisted of casting 20 prestressed rectangular concrete beams that contained two 0.6-in.-diameter (15 mm), low-relaxation prestressing strands spaced at 2 in. (50 mm) to mimic typical strand spacing. Development length was evaluated using 19 of these beams. Each beam had a cross section measuring 6.5 in. × 12 in. (165 mm × 305 mm) and was 18 ft (5.5 m) long. This specimen size was chosen based on the capacities of available equipment and may not take into account the effects of actual girder geometry. Minimum concrete cover of 2 in. (50 mm) was provided to the center of the reinforcing/prestressing steel in all directions. Shear reinforcement consisted of 0.25 in. (6.4 mm) smooth bar closed stirrups spaced at 6 in. (150 mm) on center throughout the length of the beam. Stirrups were spaced to ensure flexural failure at the expected values of embedment length. **Figure 1** shows the beam cross section.

Fourteen of the twenty beams tested were cast with two SCC mixtures, and the remaining six were cast using a conventional high-strength concrete (HSC) mixture. Each beam was given an identifying designation that includes the concrete type and a number. For example, the first beam cast using SCC with Type I cement was designated SCCI-1. All three mixtures had target initial compressive strengths at release of 7 ksi (50 MPa) and 28-day compressive strengths of 12 ksi (83 MPa). The SCC mixtures had proportions similar to those outlined by Khayat.[11] **Table 1** lists the three concrete mixture proportions. The development of the SCC proportions and the properties of these mixtures (fresh and hardened) were discussed in greater detail in an earlier paper by the authors.[12]

Each beam specimen was cast using two batches. This was due to the limited capacity of the laboratory mixer (about 9 ft^3 [0.3 m^3]). Initially, the first batch mixed 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 in. (180 mm). This ensured that all of 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 would be mixed and placed in the form. The time between the final placement of the first batch and initial placement of the second batch into the formwork was no greater than 45 minutes for all specimens. In addition, limited internal vibration was used in some instances in which ambient air temperatures caused the top layer of the first batch within the formwork to form a thin crust. This procedure ensured that both batch 1 and batch 2 for the beam specimen would be thoroughly mixed and protected against the formation of cold joints within the beam.

Each beam specimen was allowed to cure for one 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. Gradual release was accomplished by slowly relieving the pressure simultaneously in each of the hydraulic rams used during the tensioning process.

Figure 2. This photo shows the beam and load frame used for development-length tests.

Strand quality

The North American Strand Producers (NASP) strand bond test was used to assess the quality of the strand.[13,14,15] A total of 11 strand samples were tested between two separate strand reels used during beam fabrication. For the test, specimens were loaded at a constant rate of 0.100 in./min (2.54 mm/min). Concurrently, end slip was monitored using a linear voltage displacement transducer (LVDT). Load–versus–end-slip curves were generated, and the loads associated with 0.010 in. (0.254 mm) and 0.100 in. (2.54 mm) of end slip were recorded. **Table 2** shows the results of the NASP tests.

Based on the results from National Cooperative Highway Research Program (NCHRP) report 603, the recommended minimum threshold value for 0.6-in.-diameter (15 mm) prestressing strands is 12.6 kip (56.0 kN), with no individual test less than 10.8 kip (48 kN).[15] Therefore, the strand used from the two reels, which had an average pull-out force of 22.2 kip (98.8 kN) and 19.8 kip (88.1 kN) and the lowest individual test of 12.4 kip (55.2 kN), exceeded the minimum threshold value.

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.

Varied embedment lengths are used to establish bounds for the development length. 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,

Table 3. Concrete properties of SCCI beams

Beam	Fresh concrete properties			Concrete strengths		
	Slump flow, in.	T_{20}, sec	VSI	f'_{ci}, psi	f'_c, psi	f_{cld}, psi
SCCI-1	26.0	4.0	1.0	8520	13,870	16,000
	26.0	3.0	1.0			
	27.0	4.0	0.5			
SCCI-2	30.0	3.0	0.5	8700	14,420	17,390
	25.0	4.0	1.0			
	24.0	3.4	1.0			
SCCI-3	27.5	2.8	1.5	7220	11,320	13,350
	30.0	2.0	1.5			
SCCI-4	30.0	2.0	1.5	5900*	12,150	12,980
	28.0	2.8	0.5			
SCCI-5	30.0	2.6	n.d.	7430	11,420	13,550
	31.0	2.2	n.d.			
SCCI-6	28.5	3.3	n.d.	7330	11,730	14,000
	27.0	2.8	n.d.			
SCCI-7	27.0	3.9	0.5	8450	11,000	12,250
	25.5	4.2	0.5			
SCCI-8	29.5	4.6	1.5	8550	12,030	14,640
	29.0	2.5	0.5			
Average				7760	12,240	14,270

*The lower release strength for specimen SCCI-4 was due to an accidental increase in water-cement ratio.
Note: f'_c = 28-day compressive strength of concrete; f'_{ci} = compressive strength of concrete at time of release; f_{cld} = compressive strength at time of development-length testing; n.d. = no data; SCCI = self-consolidating concrete I; T_{20} = time required for the slump flow to reach a diameter of 20 in. (510 mm); VSI = visual stability index. 1 in. = 25.4 mm; 1 psi = 6.895 kPa.

strand slip occurs at the same time that the nominal moment is reached.

Test setup

The development-length flexural tests used a setup consisting of a simple-span beam loaded with a single concentrated load applied at a predetermined distance from the beam end being tested. The beam was placed within a testing frame, and load was applied using a hydraulic jack. **Figure 2** shows the load frame setup.

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 a data acquisition system while pressure was applied with a hand pump. Displacement was measured at the point of load. 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. The data acquisition equipment could read the LVDTs with an accuracy of 0.01 in. (0.25 mm).

Concrete properties

Tables 3, **4**, and **5** show the measured fresh and hardened properties of concrete for each beam. 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}, and visual stability index (VSI) 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.

Table 4. Concrete properties of SCCIII beams

Beam	Fresh concrete properties			Concrete strengths		
	Slump flow, in.	T_{20}, sec	VSI	f'_{ci}, psi	f'_c, psi	f_{cld}, psi
SCCIII-1	28.5	1.9	0.5	7080	10,920	13,330
	27.5	1.3	0.5			
SCCIII-2	26.0	1.6	0.5	6880	10,260	13,140
	25.0	1.9	0.5			
SCCIII-3	29.0	1.9	1.0	7080	10,340	13,170
	25.5	1.9	0.5			
SCCIII-4	26.5	2.4	1.0	7450	10,800	13,790
	29.0	2.5	0.5			
SCCIII-5	24.0	3.2	0.5	8230	12,880	12,550
	25.0	2.4	0.5			
Average				7540	11,420	13,200

Note: f'_c = 28-day compressive strength of concrete; f'_{ci} = compressive strength of concrete at time of release; f_{cld} = compressive strength at time of development-length testing; n.d. = no data; SCCIII = self-consolidating concrete III; T_{20} = time required for the slump flow to reach a diameter of 20 in. (510 mm); VSI = visual stability index. 1 in. = 25.4 mm; 1 psi = 6.895 kPa.

Table 5. Concrete properties of HSC beams

Beam	Fresh concrete properties	Concrete strengths		
	Slump, in.	f'_{ci}, psi	f'_c, psi	f_{cld}, psi
HSC-1	9.75	8830	12,630	15,390
	7.50			
HSC-2	9.75	8840	12,690	14,420
	10.00			
HSC-3	9.75	9920	12,510	13,430
	9.25			
HSC-4	9.75	9850	12,670	12,670
	10.00			
HSC-5	10.50	8270	10,700	13,730
	7.00			
HSC-6	9.75	9580	13,100	14,240
	9.25			
Average		9220	12,380	13,980

Note: f'_c = 28-day compressive strength of concrete; f'_{ci} = compressive strength of concrete at time of release; f_{cld} = compressive strength at time of development-length testing; HSC = high-strength concrete; n.d. = no data. 1 in. = 25.4 mm; 1 psi = 6.895 kPa.

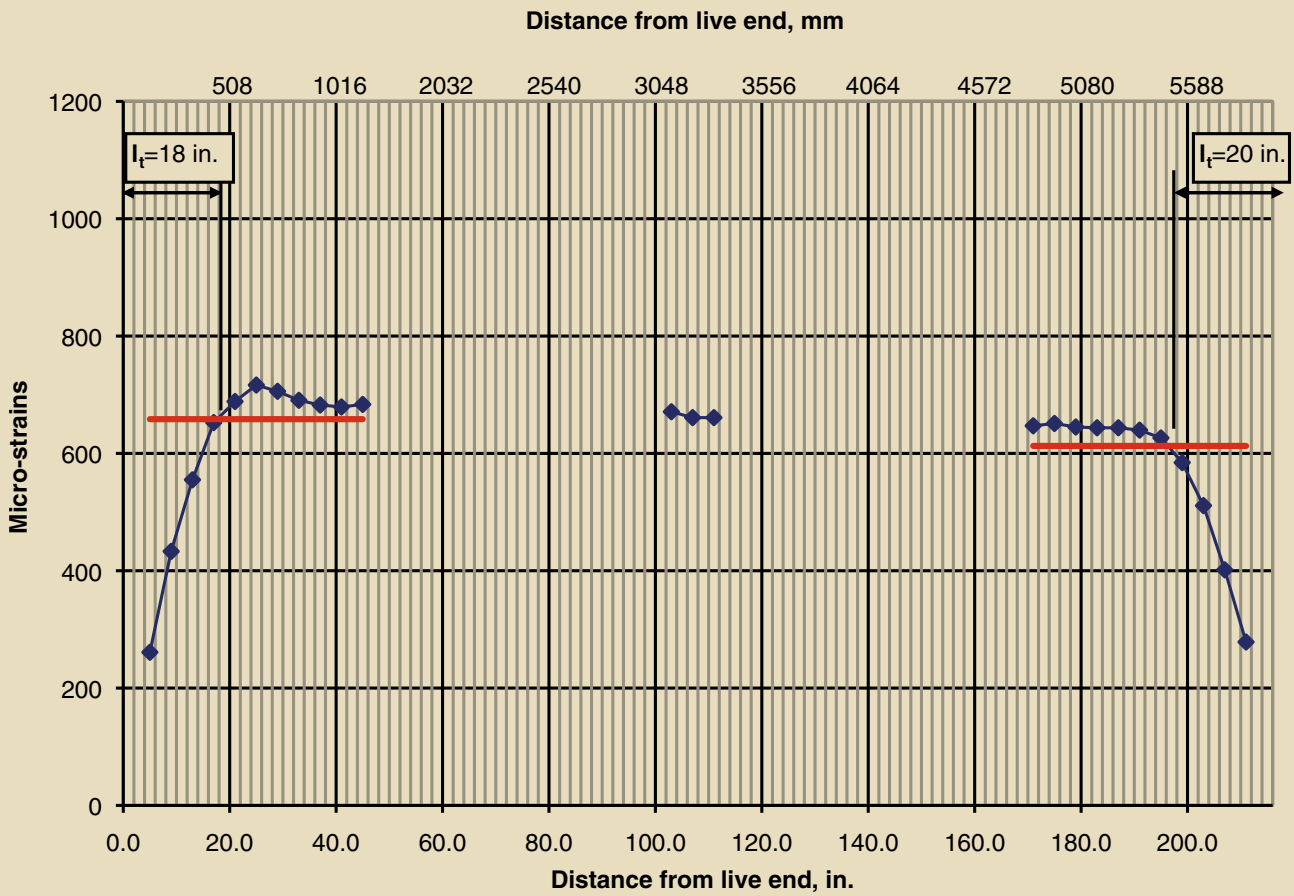

Figure 3. This graph shows the smoothed-strain profile of specimen SCCI-3, which illustrates the transfer length l_t determination using the average maximum strain method.

The compressive-strength results shown in Tables 3 through 5 represent the average of three cylinder tests from each mixture used to cast the beam. The first column, f'_{ci}, is the average concrete compressive strength at release, which was about 24 hours after casting. The second column, f'_c, is the average 28-day compressive strength of the concrete. The final column, f_{cld}, is the concrete's compressive strength at the time that the development length was evaluated. Specimen SCCI-4 exhibited a low strength at release due to an accidental increase in water content during mixing. Two more specimens were cast to make up for this discrepancy, but SCCI-4 was still tested because it reached adequate compressive strength by 28 days.

Because prestress losses were measured for some of the beams, the time at which the development length was tested ranged from 3 months to 12 months after casting. This 9-month time frame accounts for the range in compressive-strength results that were present when the flexural tests were conducted.

Transfer length

The transfer lengths l_t for all beams were reported and discussed in detail in an earlier paper by the authors.[16] However, a brief discussion of transfer lengths is included in this paper to complement the development-length results.

Transfer lengths were measured using DEMEC strain-gauge targets glued onto the beams at the center of gravity of the prestressing strands. The targets were spaced at 4 in. (100 mm) increments. A gauge was used to periodically measure changes in distance between the targets up to 28 days of age. The concrete surface strains were calculated by measuring the change in distance between DEMEC targets. The strains were then graphed, and the 95% average maximum strain method was employed to determine transfer lengths for all beams.[17] **Figure 3** illustrates the 28-day smoothed-strain profile for SCCI-3. **Tables 6**, **7**, and **8** show the measured transfer lengths and the calculated values. The research results showed that there was little difference between the transfer lengths for the conventional HSC beams and the high-strength SCC beams. The results also showed that the transfer lengths were 60% and 56% of those predicted by the ACI 318-08 and AASHTO LRFD specifications.

Development-length results

Experimental determination of development length is an iterative process. Flexural-load tests were performed in

Table 6. Transfer lengths at 28 days for SCCI beams

Specimen	f_{se}, ksi	Transfer length, in.					Measured / ACI/AASHTO	
		Measured		ACI/AASHTO $^1/_3 f_{se} d_b$	ACI $50d_b$	AASHTO $60d_b$		
		Live end	Dead end				Live end	Dead end
SCCI-1	175.9	28.0	28.0	35.2	30.0	36.0	0.80	0.80
SCCI-2	175.9	26.0	n.d.*	35.2	30.0	36.0	0.74	n.d.
SCCI-3	184.4	18.0	20.0	36.9	30.0	36.0	0.49	0.54
SCCI-4	180.1	23.0	21.0	36.0	30.0	36.0	0.64	0.58
SCCI-5	183.5	20.0	22.0	36.7	30.0	36.0	0.55	0.60
SCCI-6	183.1	17.0	17.0†	36.6	30.0	36.0	0.46	0.46
SCCI-7	179.5	21.0	23.0	35.9	30.0	36.0	0.58	0.64
SCCI-8	181.6	21.0	17.0	36.3	30.0	36.0	0.58	0.47
Average	n.a.	21.8	21.1	36.1	n.a.	n.a.	0.60	0.58

*Dead-end transfer-length data for beam SCCI-2 were erratic.
†Several DEMEC targets were lost on one side of beam SCCI-6 at the dead end; therefore, the reported transfer length is only based on DEMEC strain gauge data from one side.
Note: AASHTO = American Association of Highway and Transportation Officials; ACI = American Concrete Institute; d_b = nominal diameter of strand; f_{se} = effective stress in prestressing steel after all losses; n.d. = no data; n.a. = not applicable; SCCI = self-consolidating concrete I. 1 in. = 25.4 mm; 1 ksi = 6.895 MPa.

Table 7. Transfer lengths at 28 days for SCCIII beams

Specimen	f_{se}, ksi	Transfer length, in.					Measured / ACI/AASHTO	
		Measured		ACI/AASHTO $^1/_3 f_{se} d_b$	ACI $50d_b$	AASHTO $60d_b$		
		Live end	Dead end				Live end	Dead end
SCCIII-1	177.0	20.0	19.0	35.4	30.0	36.0	0.56	0.54
SCCIII-2	176.6	24.0	21.0	35.3	30.0	36.0	0.68	0.59
SCCIII-3	175.8	15.0	15.0	35.2	30.0	36.0	0.43	0.43
SCCIII-4	176.0	17.0	18.0	35.2	30.0	36.0	0.48	0.51
SCCIII-5	176.2	22.0	26.0	35.2	30.0	36.0	0.62	0.74
SCCIII-6*	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Average	n.a.	19.6	19.8	35.3	n.a.	n.a.	0.56	0.56

*Transfer-length data for beam SCCIII-6 were erratic.
Note: d_b = nominal diameter of strand; f_{se} = effective stress in prestressing steel after all losses; n.a. = not applicable; n.d. = no data; SCCIII = self-consolidating concrete III. 1 in. = 25.4 mm; 1 ksi = 6.895 MPa.

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: six cast with HSC, eight with SCCI, and five with SCCIII. **Table 9** summarizes the results of the flexural tests.

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

Table 8. Transfer lengths at 28 days for HSC beams

Specimen	f_{se}, ksi	Transfer length, in.					Measured / ACI/AASHTO	
		Measured		ACI/AASHTO $^1/_3 f_{se} d_b$	ACI $50d_b$	AASHTO $60d_b$		
		Live end	Dead end				Live end	Dead end
HSC-1	183.8	n.d.*	20.0	36.8	30.0	36.0	n.d.	0.54
HSC-2	183.2	19.0	17.0	36.6	30.0	36.0	0.52	0.46
HSC-3	182.1	25.0	26.0	36.4	30.0	36.0	0.69	0.71
HSC-4	182.0	24.0	26.0	36.4	30.0	36.0	0.66	0.71
HSC-5	180.9	26.0	29.0	36.2	30.0	36.0	0.72	0.80
HSC-6	180.4	26.0	23.0	36.1	30.0	36.0	0.72	0.64
Average	n.a.	24.0	23.5	36.4	n.a.	n.a.	0.66	0.65

*Live-end 28-day transfer length data for beam HSC-1 were erratic.
Note: d_b = nominal diameter of strand; f_{se} = effective stress in prestressing steel after all losses; HSC = high-strength concrete; n.a. = not applicable; n.d. = no data. 1 in. = 25.4 mm; 1 ksi = 6.895 MPa.

moment when slip occurred M_{slip} with the nominal moment allowed a good range of values to be developed as an estimate of the development length for each different concrete type. While M_{slip} was compared with M_n to determine the relationship of the embedment length to the development length, the maximum moment M_{max} achieved for each beam was typically greater than the nominal moment. However, these ranges were not without some question because shear failure of SCCIII specimens at short embedment lengths made determination of the development length somewhat difficult. Also, slippage below and above the nominal moment for specimens at certain embedment lengths in each group complicated the determination of results. The fact that development length was considered to be the embedment length where strand slip occurs at the same time the specimen reaches nominal moment caused these difficulties.

For the HSC specimens, testing began at an embedment length of 47 in. (1200 mm) for HSC-6 and at 40 in. (1020 mm) for HSC-4. Both beams failed in flexure with no strand slip at moments that were 20% to 25% greater than the nominal moment. **Figure 4** shows a pure flexural failure with no slip for specimen HSC-1. Because no strand slip occurred in these specimens, the embedment length was shortened to 35 in. (890 mm) for HSC-1.

Next, HSC-2 and HSC-5 were tested at an embedment length of 30 in. (760 mm), and strand slip occurred in both beams. 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. **Figure 5** shows a flexural failure resulting after slip had occurred at less than the nominal moment for specimen HSC-5. From these 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 in. and 35 in.

Both SCCI specimens, SCCI-3 and SCCI-6, tested at an embedment length of 40 in. (1020 mm) failed without detection of strand slip. Specimen SCCI-4, tested at an embedment length of 35 in. (890 mm), exhibited strand slip at a moment 13% below the nominal moment. However, SCCI-8 was also tested with an embedment length of 35 in., and this specimen experienced no slip and failed in flexure at a moment 16% greater than the nominal moment.

For SCCI-1 and SCCI-2, the embedment length was increased to 37.5 in. (950 mm). Specimen SCCI-1 exhibited strand slip at a moment 3% below the nominal moment. Conversely, SCCI-2 was tested at an embedment length of 37.5 in. (950 mm) and exhibited strand slip at a moment 7% greater than the nominal moment. This leads to the conclusion that the development length is near 37.5 in. and is most likely between 35 in. and 37.5 in.

The SCCIII specimens were the last series of beams tested. For these beams, no slip was detected in specimens SCCIII-2 and SCCIII-4, which were tested at an embedment length of 35 in. (890 mm). Specimen SCCIII-5 was tested at an embedment length of 30 in. (760 mm) 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 was difficult to interpret this result. **Figure 6** shows failure of specimen SCCIII-5, with strand slip occurring after a shear crack developed in the transfer zone.

Specimens SCCIII-1 and SCCIII-3 were subsequently tested at an embedment length of 32.5 in. (826 mm). Specimen SCCIII-1 exhibited slip at a moment 21% greater than the nominal moment, while specimen SCCIII-3 exhibited slip

Table 9. Development-length results

Beam ID	L_E, in.	M_n, kip-in.	M_{slip}, kip-in	M_{max}, kip-in.	M_{slip}/M_n	M_{max}/M_n
HSC-1	35	1076	n.d.	1322	n.d.	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	n.d.	1268	n.d.	1.20
HSC-5	30	1063	990	1213	0.93	1.14
HSC-6	47	1067	n.d.	1337	n.d.	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	n.d.	1274	n.d.	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	n.d.	1305	n.d.	1.23
SCCI-7	45	1050	n.d.	1195	n.d.	1.14
SCCI-8	35	1070	n.d.	1242	n.d.	1.16
SCCIII-1	32.5	1059	1285	1300	1.21	1.23
SCCIII-2	35	1058	n.d.	1351	n.d.	1.28
SCCIII-3	32.5	1058	1043	1107	0.99	1.05
SCCIII-4	35	1063	n.d.	1283	n.d.	1.21
SCCIII-5	30	1052	999.8	1021	0.95	0.97

Note: L_E = embedment length; M_{max} = maximum moment resisted by the beam; M_n = nominal moment capacity; M_{slip} = moment when strand slip occurred; n.d. = no data. 1 in. = 25.4 mm; 1 kip-in. = 0.1130 kN-m.

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 (the applied moment of 1107 kip-in. [125 kN-m] dropped to 1043 kip-in. [118 kN-m], at which point the shear failure and strand slip occurred). The width of the shear cracks was not measured, but it was noted that in all cases of shear cracks propagating into the anchorage, strand slip soon resulted. Shear reinforcement should be increased near the supports for future testing. From this data, it can be determined that the development length for the SCCIII specimens is less than 32.5 in. (825 mm) and is most likely near but greater than 30 in. (760 mm). More testing should be done for SCCIII specimens to validate the 30 in. (760 mm) lower boundary.

Development-length comparisons

Both the ACI 318-08 and AASHTO LRFD specifications estimate development length using the relationship

$$l_d = \left(\frac{f_{se}}{3}\right)d_b + \left(f_{ps} - f_{se}\right)d_b$$

where

l_d = development length

f_{se} = effective stress in the strands after all prestress losses

f_{ps} = stress in the strand at nominal flexural strength

d_b = nominal diameter of prestressing strand

Table 10 compares the calculated values obtained using this equation and the embedment-length values determined from the testing. This table also includes values of f_{se} and f_{ps} obtained from calculations based on strain compatibility. The concrete strength at the time of testing was used to calculate both f_{ps} and the nominal moment for the beams in order to have a closer representation of

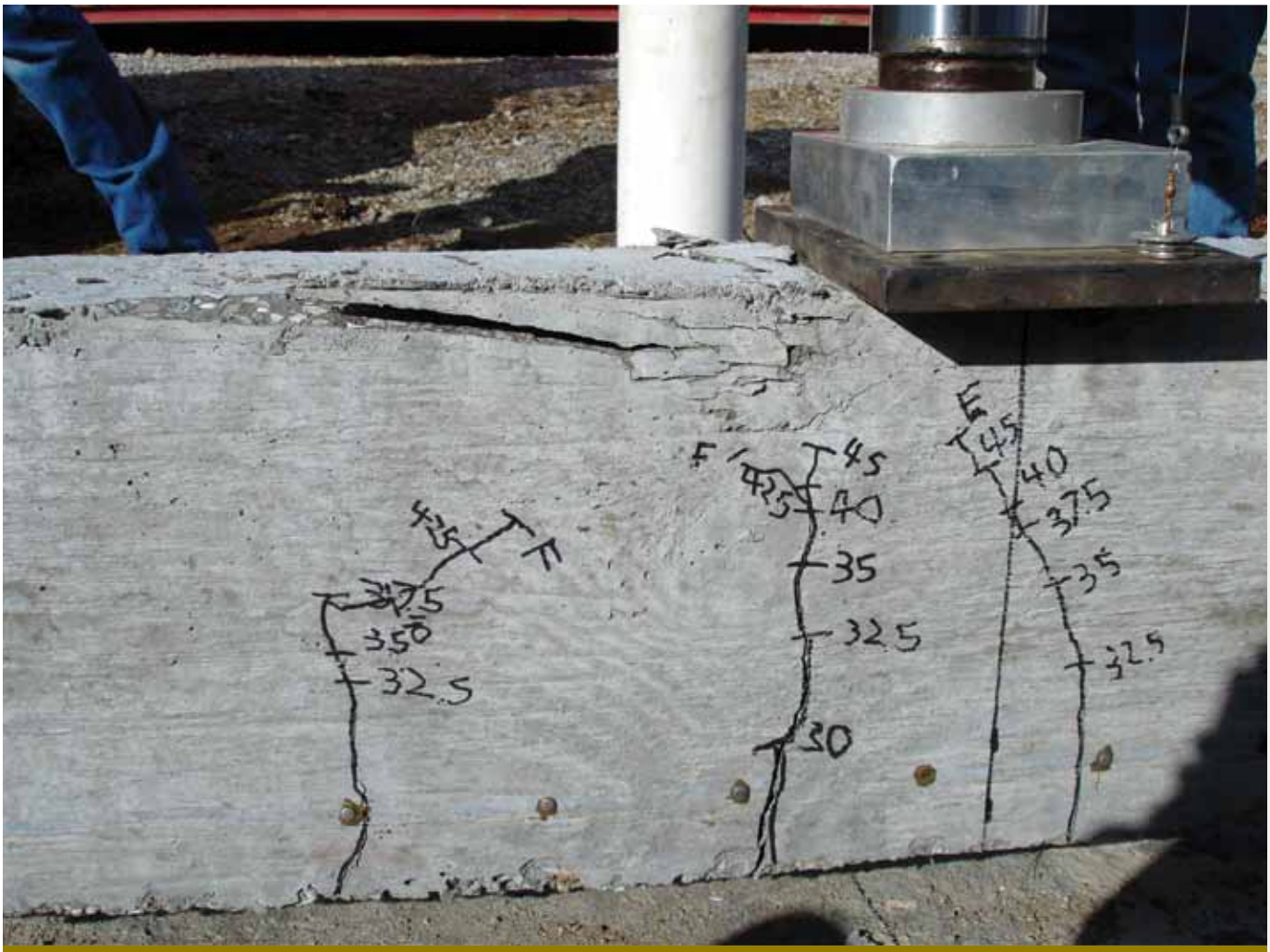

Figure 4. This photo shows the failure of beam HSC-1, which illustrates flexural failure with no measured slip.

actual conditions. This should give a good comparison between the equation and the actual behavior at time of testing. The elapsed time between the first tests and the final tests did cause some differences in compressive strengths.

This table shows that the development-length predictions using the ACI-AASHTO equation are significantly greater than those found experimentally. An experimentally estimated development length between 30 in. and 35 in. (760 mm and 890 mm) was found for HSC specimens, in contrast to the prediction of between 86.3 in. and 88.4 in. (2190 mm and 2250 mm). This is an overestimation of 60% to 66%.

The SCCI specimens had an experimentally determined development length of 35 in. to 37.5 in. (890 mm to 950 mm), while the prediction was 86.1 in. to 88.3 in. (2190 mm to 2240 mm). This is an overestimation of 60% to 66% as well. The SCCIII specimens had an experimentally determined development length of 30 in. to 32.5 in. (760 mm to 826 mm), while the prediction was 89.2 in. to 89.4 in. (2266 mm to 2271 mm). This is an overestimation of 64% to 67%.

The NCHRP 603 report presents a method of incorporating the compressive strength of the concrete into the development-length predictions.[15] This method uses the following relationship:

$$l_d = \left(\frac{120}{\sqrt{f'_{ci}}}\right)d_b + \left(\frac{225}{\sqrt{f'_c}}\right)d_b \geq 100d_b$$

where

f'_{ci} = concrete strength at release

f'_c = design concrete strength

The relationship applies to HSC with a limiting compressive strength of 9 ksi (62 MPa) at release and a design compressive strength of 14 ksi (97 MPa).[15] Comparisons were made with this development-length estimation using the concrete strength at the time of testing. The limiting strengths were used when the concrete strength exceeded these values. For HSC specimens, the NCHRP equation predicted development lengths between 60.3 in. and 61.9

Figure 5. This photo shows the failure of beam HSC-5, which illustrates flexural failure after slip below the nominal moment.

in. (1530 mm and 1570 mm). This is an overestimation of 42% to 52%. The development-length estimates for SCCI specimens were between 60.5 in. and 63.7 in. (1540 mm and 1620 mm). This is an overestimation of between 38% and 45%. Development lengths of SCCIII specimens were predicted to be between 62.7 in. and 64.7 in. (1590 mm and 1640 mm), which is an overestimation of 48% to 54%.

Neglecting the limitations of this relationship yielded slightly lower development-length predictions for the HSC and SCCI specimens, but these still exceeded the measured values by at least 34%. While this incorporation of the effects of compressive strength does yield predictions that are closer to the measured values, the predictions based on the NCHRP equation are still conservative.

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. The average concrete compressive strengths for HSC and SCCI were similar, 14.51 ksi (100.0 MPa) for HSC and 14.77 (101.8 MPa) for SCCI, while the average compressive strength of SCCIII was somewhat lower, 13.19 ksi (90.9 MPa). **Figure 7** shows a comparison of both predicted and measured development lengths. The results obtained from this study indicate that conventional high-strength concrete and high-strength SCC yield similar development lengths for 0.6-in.-diameter (15 mm) prestressing strand. Some previous research has also shown similar behavior between conventional concrete and SCC.[3,7] The ACI-AASHTO equation is conservative for both HSC and SCC. However, this research was conducted on specimens having high concrete strengths along with the ideal case of gradual strand release. These factors, along with the high bond quality of the prestressing strand used, indicate that the results of this research are not necessarily applicable to lower concrete strengths or prestressing strand with lower bond quality.

Figure 6. This photo shows the failure of beam SCCIII-5, which illustrates shear failure with strand slip immediately following.

Conclusion

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 in. (950 mm).
- 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%.
- The NCHRP 603 equation overestimated the development length for HSC and SCCI beams by about 40% and for SCCIII beams by about 50%.
- All three concrete mixtures achieved similar differences between calculated nominal moment and applied moment at failure.

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Table 10. Measured versus predicted development lengths

Beam	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

Note: f_{ps} = stress in prestressing steel at nominal flexural strength; f_{se} = effective stress in prestressing steel after all losses; l_d = development length; L_E = embedment length. 1 in. = 25.4 mm; 1 ksi = 6.895 MPa.

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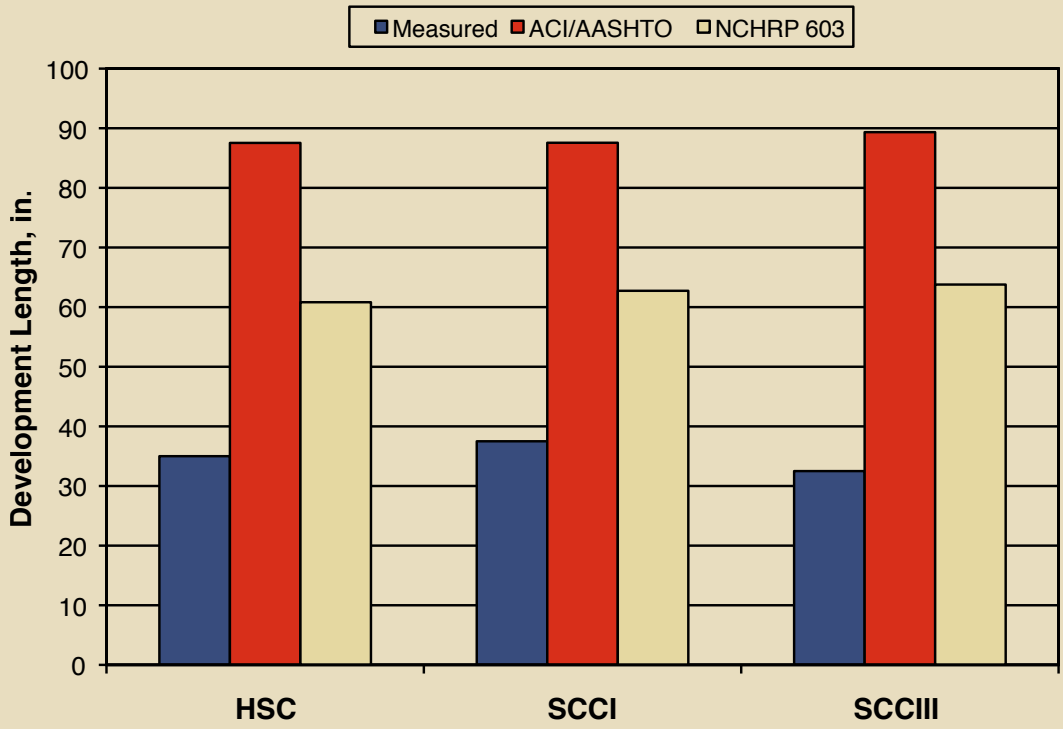

Figure 7. This graph shows the measured and predicted development lengths. Note: 1 in. = 25.4 mm.

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Notation

d_b = nominal diameter of strand

f'_c = 28-day compressive strength of concrete

f'_{ci} = compressive strength of concrete at time of release

f_{cld} = compressive strength of concrete at time of development-length testing

f_{ps} = stress in prestressing steel at nominal flexural strength

f_{se} = effective stress in prestressing steel after all losses

l_d = development length

l_t = transfer length

L_E = embedment length

M_{max} = maximum moment resisted by the beam

M_n = nominal moment capacity

M_{slip} = moment when strand slip occurred

T_{20} = time required for the slump flow to reach a diameter of 20 in. (500 mm)

w/c = water-cement ratio

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Synopsis

Self-consolidating concrete (SCC) is a type of concrete that can be placed without consolidation and is becoming widely accepted. The constituent materials of SCC differ little from conventional concrete. However, SCC typically contains more fine aggregate and cement but less coarse aggregate. These differences may affect the development length of prestressing steel and flexural bond performance for SCC specimens compared with conventional concrete specimens.

This research program compares the measured development lengths of SCC members to those of conventional high-strength concrete. A total of 20 beam specimens containing two 0.6-in.-diameter (15 mm) prestressing strands were tested. The beam specimens measured 6.5 in. × 12 in. (165 mm × 300 mm) and were 18 ft (5.5 m) long. Fourteen beams were cast with SCC, while the remaining six beams were cast with a high-strength concrete. The targeted release strength for all girders was 7000 psi (48 MPa), and the 56-day strength for all girders was 12,000 psi (83 MPa). The development lengths for all beams were between 30 in. and 40 in. (760 mm and 1000 mm).

Keywords

Design, development length, flexural bond, high-strength concrete, prestressing, self-consolidating concrete, strand bond.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

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