EFFECT OF CONCRETE COMPRESSIVE STRENGTH ON TRANSFER LENGTH AND DEVELOPMENT LENGTH

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ABSTRACT

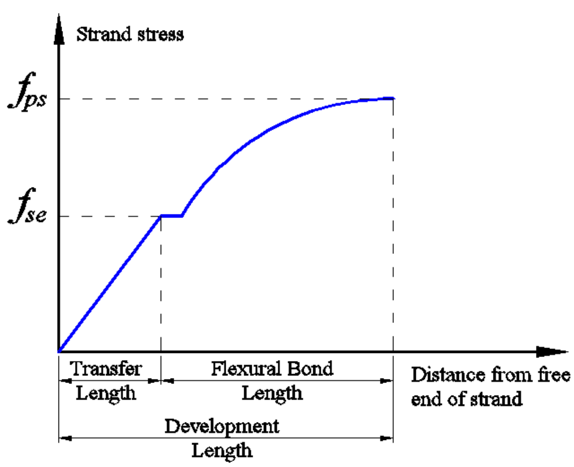
The proposed research paper examines the effect of concrete compressive strength on the transfer length and development length of prestressing strands. The paper includes the results from several research projects conducted at the University of Arkansas (UA). At the UA, 57 prestressed, precast beams have been cast since 2005. These beams measure 6.5 in. by 12 in. by 18 ft. in length. The beams were cast with self-consolidating concrete (SCC), high strength concrete (HSC), lightweight self-consolidating concrete (LWSCC), and ultra-high performance concrete (UHPC). The compressive strengths at release ranged from 3400 psi to 22,540 psi. The 28 day strengths ranged from 5000 psi to 28,830 psi. The beams contained two, low relaxation, Gr. 270 prestressing strands. Strand diameters of 0.5 in. and 0.6 in. were included in the study. The results showed that transfer lengths increased when the compressive strength at release was less than 5000 psi. However, when the compressive strength at release was greater than 5000 psi, there was little difference in transfer length. Similar trends were apparent in the development length results.

Keywords: Transfer length, Development length, High strength concrete, Self-consolidating concrete, Ultra-high performance concrete, Effect of concrete.

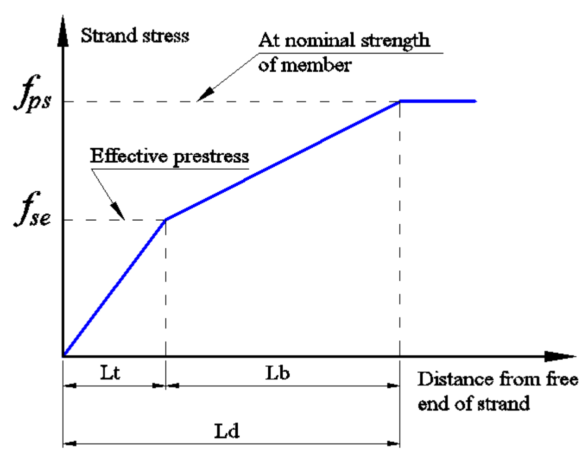
BACKGROUND

Investigations in transfer and development lengths began when Hanson and Kaar published their investigations in 1959 [1]. Later, the American Concrete Institute Building Code (ACI 318) in 1963 implemented equations for these lengths such that these equations have been used to determinate the transfer and development lengths in prestressed concrete designs [2]. These equations presented by ACI were adopted in 1973 by the American Association of State and Highway Transportation Officials (AASHTO) Specifications [3]. Early investigations used stress-relieved Grade 250 strand with an ultimate strength, f_{pu}, of 250 ksi which typically was tensioned to approximately $0.70f_{pu}$. Currently, low relaxation, Grade 270 strands, are used and have been tensioned of to $0.80f_{pu}$ [4, 5]. Research shows that major improvements have been made in prestressed concrete which include higher strength concretes with greater pretensioning stresses and larger strand sizes than those tested in the earliest investigations[4, 5].

Fig. 1 illustrates an idealization of strand stress versus length for pretensioned strand. The flexural bond length is defined as the additional length required to develop the strand tension necessary to resist external loads. Both transfer length and flexural bond length give the development length defined not only in ACI 318-11, Section 12.9-*Development of prestressing strand*, but also in AASHTO LRFD, Section 5.11.4.2-*Bonded Strand* [2, 3].



(a) Early considerations



(b) ACI and AASHTO assumption

Fig. 1 Strand stress vs. length, ACI 318-11 (R12.9) and AASHTO LRFD (C5.11.4.2-1)

The equation for transfer length given by ACI 318 Building Code (Commentary Section R12.9) is written as follows

$$L_t = \frac{f_{se}}{3} d_b \tag{1}$$

where:

L_t = transfer length (in.)

f_{se} = effective prestressing stress after all losses (ksi)
d_b = strand diameter (in.)

In sections 11.3.4 and 11.3.5, ACI 318-11 defines transfer length as 50 strand diameters ($50d_b$), and the development length is the sum of the transfer length and the flexural bond length. The flexural bond length is defined by

$$L_b = (f_{ps} - f_{se})d_b \tag{2}$$

where:
L_b = flexural bond length (in.)
f_{se} = effective prestressing stress after all losses (ksi)
f_{ps} = strand stress at nominal strength of member (ksi)
d_b = strand diameter (in.)

The development length equation given by ACI 318-11 in section 12.9 is the following

$$L_d = \frac{f_{se}}{3} d_b + (f_{ps} - f_{se})d_b = \left(f_{ps} - \frac{2}{3} f_{se} \right) d_b \tag{3}$$

Although AASHTO LRFD adopted the same equations for transfer and development lengths given by ACI 318 Building Code, AASHTO LRFD has specified that the transfer length can be taken as 60 strand diameters ($60d_b$) (Article 5.11.4.1). The development length written in Eq. (4) must be taken as specified in its Article 5.11.4.2. In this equation, a k factor has been added according to the recommendation of the 1988 FHWA memorandum.

$$L_d = k\left(f_{ps} - \frac{2}{3} f_{se} \right) d_b \tag{4}$$

Where:
L_d = development length (in.)
f_{se} = effective prestressing stress after all losses (ksi)
f_{ps} = strand stress at nominal strength of member (ksi)
d_b = strand diameter (in.)
k = 1.0 for pretensioned panels, piles, and other pretensioned members with a depth < 24 inches.
k = 1.6 for pretensioned members with a depth ≥ 24 inches.
k = 2.0 for debonded strand (Article 5.11.4.3)

Fig. 2 shows how the transfer and development length should be considered in a simply supported beam subjected to a uniformly distributed load. From Fig. 2 we can see that the transfer length due to the initial prestress is greater than the transfer length due to the effective prestress in the strand after all prestress losses [4-8]. Thus, the development length may increase if the flexural bond length is the same in both cases.

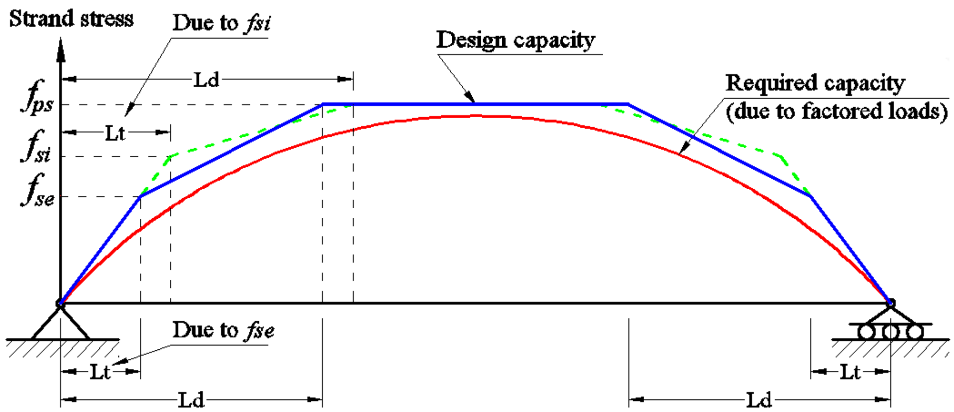


Fig. 2 Schematic representations of transfer and development lengths for a simply supported beam

Investigations have focused on transfer and development lengths by considering different variables since the 1950s. Equations developed from these investigations have been published, but many have never been considered for the ACI 318 Building Code or AASHTO LRFD. Some of equations give values less than the ACI Code and AASHTO LRFD, and some very conservative when compared to the ACI Code or AASHTO LRFD. Therefore, the transfer and development lengths given in the ACI Code and AASHTO LRFD have been argued due to the fact that the transfer length and the flexural bond length are a function of the strand stress, which is the effective prestress in the strand after all losses (f_{se}) and strand stress at nominal strength of the member (f_{ps}), and strand diameter (d_b) [2, 3]. On the other hand, current investigations have shown variables such as initial prestress (f_{si}), concrete compressive strength at release (f'_{ci}) and at 28-day (f'_c) contribute to both lengths [5, 8-11]. For instance, for high strength concrete the transfer and development lengths are less than ACI Code and AASHTO LRFD [5, 10, 12]. These results suggest that concrete compressive strength should be considered and included as well as the strand stress at release and at 28-day.

RESEARCH OBJECTIVES

This research program examined the transfer and development lengths for over 50 beam specimens cast at the University of Arkansas. These beams were cast with a variety of concrete types (SCC, lightweight, HSC, etc) at a wide range of compressive strengths. The paper focuses on the effect of concrete compressive strength on transfer and development length.

EXPERIMENTAL PROGRAM

The beams were fabricated at the Engineer Research Center (ERC) at the University of Arkansas (UA). Researchers at the UA have examined transfer and development length on a variety of concrete types which resulted in a wide range of concrete compressive strengths. Fifty-seven (57) fully bonded prestressed, precast beams have been cast since 2005. Each beam had a rectangular cross-section of 6.5 in. by 12 in. and 18 ft. in length. The beams contained two, low relaxation wire Gr. 270 prestressing strand, located a distance of 10 in. from the extreme compression fiber. The strands were tensioned to $0.75f_{pu}$ before release. Strand diameters of 0.5 in. and 0.6 in. were included in the study. Two No. 6 Gr. 60 reinforcing bars were located 2 in. from the extreme compressive fiber. The beams also contained 1/4 in. diameter smooth bars shear stirrups spaced at 6 in. on center. This ensured either flexural or bond failures. Shown in Fig. 3 are the beam details. The beams were cast with normal strength concrete (NSC), self-consolidating concrete (SCC), high strength concrete (HSC), lightweight slef-consolidating concrete (LWSCC), or ultra-high performance concrete (UHPC) [13-16]. The compressive strengths at release ranged from 3400 psi to 22,540 psi, and the 28 day strengths ranged from 5000 psi to 28,830 psi.

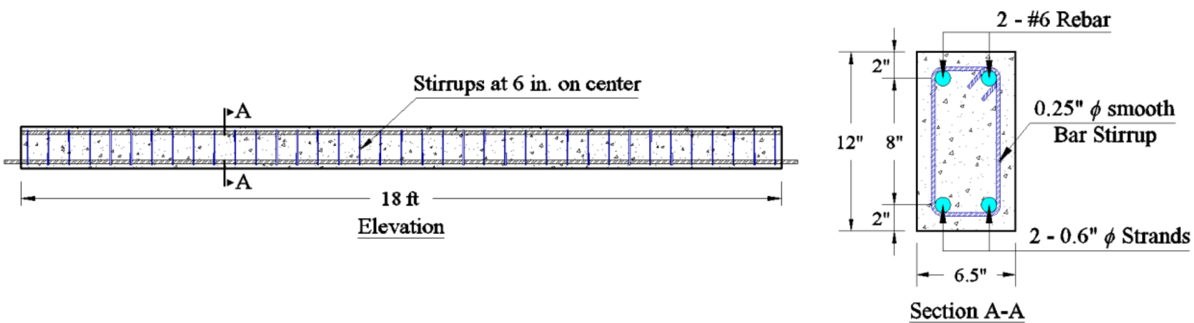


Fig. 3 Beam specimen details

The number and type of beam cast is presented in Table 1. Also shown in Table 1 is the number of tests for transfer and development in each beam series. Fifty one of the fifty seven beams tested were cast with two, 0.6 in. diameter [13-15], Gr. 270, low-relaxation prestressing strands spaced at 2 in. to mimic typical strand spacing. The remaining 6 beams were cast with two 0.5 in. diameter strands (Gr. 270, low relaxation) [16]. The number of transfer length tests for 0.6 in. strand was 102 and there were 76 development length tests. The remaining transfer and development tests were conducted on beams containing 0.5 in. diameter strands. For the NSCL, NSS, NSL, HSCL, HSS, and HSL beam series, both beam ends were tested for determining development length. For the remaining series, only one beam end was tested.

Table 1 Number of trial beams and tests for transfer and development lengths

Series	**Number of Beams**	**Number of tests**	
		L_t	**L_d**
NSCL: Normal strength clay	4	8	8
NSS: Normal strength shale	5	10	10
NSL: Normal strength limestone	4	8	8
HSCL: High strength clay	4	8	8
HSS: High strength shale	4	8	8
HSL: High strength limestone	4	8	8
SCCI: Self-consolidating concrete type I	8	16	8
SCCIII: Self-consolidating concrete type III	5	10	5
HSC: High strength concrete	6	12	6
UHPC: Ultra high performance concrete	7	14	7
LWSCC (*): Lightweight self-consolidating concrete	6	12	6
Total	**57**	**114**	**82**

(*) Strand 0.5 in. diameter

Concrete mixtures proportions for each type of concrete used to cast the beams are presented in Table 2.a and 2.b**.** The development of these mixtures and their properties (fresh and hardened) were discussed in greater detail in earlier publications by the authors [12-16, 18-21].

Table 2.a: Concrete mixture proportions

Material	**NSCL**	**NSS**	**NSL**	**HSCL**	**HSS**	**HSL**
Cement (lb/yd^3)	825	850	775	808*	832*	825
Fly ash (lb/yd^3)	---	---	---	142	147	---
Coarse Agg. (lb/yd^3)	649	748	1408	649	703	1392
Fine Agg. (lb/yd^3)	1407	1437	1481	1242	1270	1403
Water (lb/yd^3)	329	298	310	333	333	330
HRWR (oz/cwt)	6.0 - 6.5	5.0 - 6.0	4.5 - 7.0	10 - 14	10 - 11	6
w/cm	0.40	0.35	0.40	0.35	0.34	0.40
Slump flow (in.)	25 - 28	26 - 29.5	19 - 27	25.5 - 29	26.0 - 30.5	26 - 28
T20 (sec)	3.4 - 5.4	2 - 6.4	2 - 3.2	5.0 - 11.2	1.4 - 4.8	2.0 - 2.8
J-Ring Δh (in.)	1.25 - 2.25	1.25 - 2.25	1.0 - 2.25	1.0 - 2.0	0.50 - 1.75	0.50 - 1.0

Note: 1 lb = 0.454 kg, 1 oz = 29.54 mL, 1 yd^3 = 0.765 m^3, 1 in. = 25.4 mm, 1 psi = 0.006895 MPa, 1 ft^3 = 0.0283 m^3. (*) cement Type III. HRWR: High-range Water Reducers

Table 2.b: Concrete mixture proportions

Material	**SCCI**	**SCCIII**	**HSC**	**UHPC**	**LWSCC**
Ductal ® Premix (lb/yd^3)	---	---	---	3697	---
Cement (lb/yd^3)	950	808*	900	---	792
Fly ash (lb/yd^3)	---	142	---	---	---
Coarse Agg. (lb/yd^3)	1350	1350	1800	---	668
Fine Agg. (lb/yd^3)	1474	1400	1207	---	1238
Water (lb/yd^3)	285	304	234	219	391
HRWR (oz/cwt)	(**)	(**)	(**)	51	7.5
w/cm	0.30	0.32	0.26	---	0.49
Slump flow (in.)	25.0 - 31.0	24.0 - 29.0	7.5 - 10.5	---	19.0 -24.5
T_{20} (sec)	2.0 - 4.6	1.3 - 3.2	---	---.	4.11 - 7.21
J-Ring Δh (in.)	---	---	---	---	17.5 - 25.5
Steel fibers (lb/yd^3)	---	---	---	263	---

Note: 1 lb = 0.454 kg, 1 oz = 29.54 mL, 1 yd^3 = 0.765 m^3, 1 in. = 25.4 mm, 1 psi = 0.006895 MPa, 1 ft^3 = 0.0283 m^3. (*) cement Type III. (**): HRWR-admixtures were a combination of poly carboxylate admixtures and viscosity modifying admixtures.

Strands for all specimens were gradually released at approximately 24 hours of age. This was accomplished by releasing the pressure in the hydraulic strand tensioning system. Each beam specimen was labeled using a designation for the concrete type along with a number. For instance, the first beam cast using SCC with Type I cement was labeled SCCI-1 [19-21]. The minimum, maximum, and average of the concrete compressive strength at release and 28 days of age as well as the effective strand stress after all losses are presented in Table 3.

Table 3 Concrete compressive strength and effective strand stress for each series

Series	Reported Concrete Strength Release: f'_{ci} (ksi)			Reported Concrete Strength 28-Day: f'_c (ksi)			Reported Effective Strand Stress: f_{se} (ksi)		
	Min.	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**
NSS	3.40	4.05	4.45	5.00	6.12	6.70	151.0	156.0	158.0
NSCL	4.02	4.42	5.16	5.04	5.69	6.70	151.9	155.1	160.2
NSL	4.10	4.75	5.48	6.71	7.59	7.97	166.4	169.1	171.9
HSS	5.53	6.03	6.93	6.42	7.02	8.06	163.3	166.1	170.2
HSCL	5.96	6.21	6.41	6.71	7.12	7.54	166.8	167.4	167.9
HSL	6.83	6.91	7.02	8.85	9.25	9.70	176.0	176.2	176.4
SCCIII	6.88	7.35	8.24	10.26	11.04	12.89	175.6	176.3	177.0
SCCI	5.90	7.76	8.70	11.00	12.24	14.42	175.3	180.5	184.4
HSC	8.83	9.32	9.92	10.70	12.39	13.10	180.4	182.2	183.3
UHPC	12.77	17.96	22.54	17.19	26.39	28.83	185.1	188.1	189.9
LWSCC (*)	3.50	4.56	5.39	5.92	6.66	7.48	167.5	172.0	176.1

(*): Strand 0.5-in. diameter was used in this case

Transfer lengths were measured with detachable mechanical (DEMEC) strain gage targets attached to the concrete at the center of gravity of the prestressing strand. The DEMEC targets were affixed to the beams before prestress release, and they were placed on both ends of the beam on both faces (Fig. 4) [8, 9, 22-25]. The first target was placed at 1 in. from the end of the beam, and the other DEMEC points were placed at 4 in. interval. LVDTs were placed on each strand at the ends of the beam. This allowed strand movement to be monitored during development length testing.

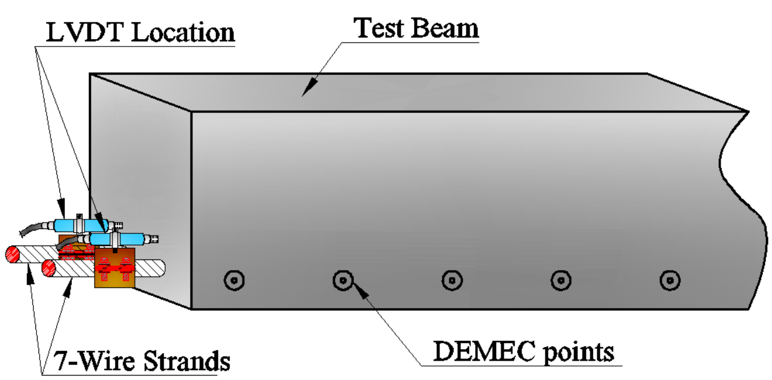


Fig. 4 Instrumentation scheme for slip measurement

The measured transfer lengths for all beams and for both ends (dead end and live end) are shown in Fig. 5. The relationship between concrete compressive strength (at release and 28 days) and measured transfer length (at release and 28 days) is shown in Fig. 6.

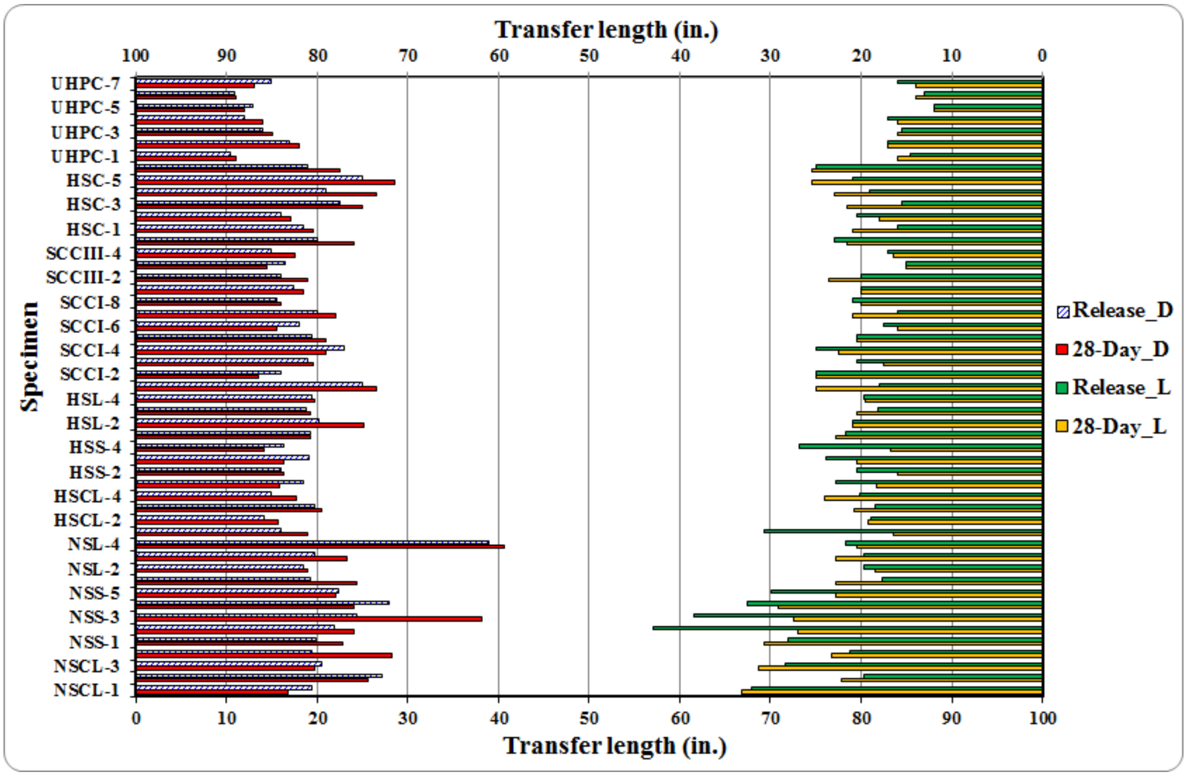


Fig. 5 Transfer length at dead end and live end for all number of tests (strand 0.6 in.)

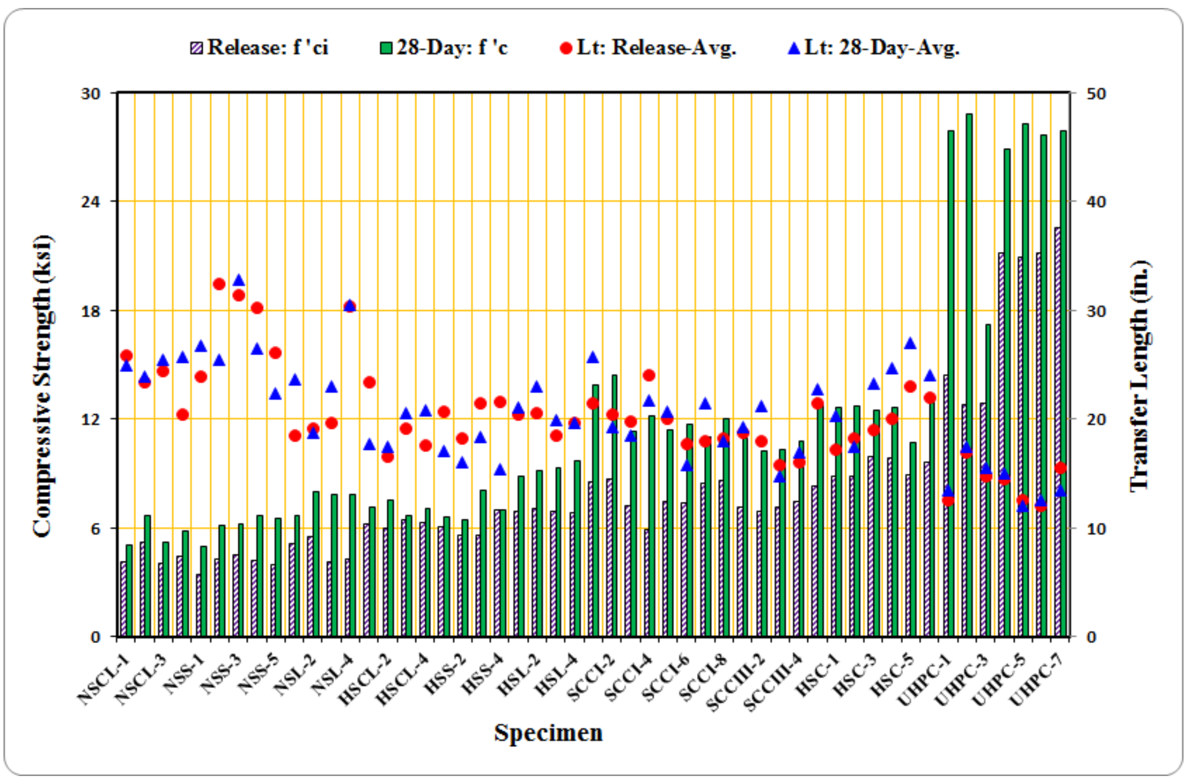


Fig. 6 Concrete compressive strength and transfer length relationship at release and 28-day

The figures shown above show that beams with lower compressive strength at either release or 28 days also had the higher transfer lengths. On the contrary, smaller transfer lengths were measured in beams with high compressive strength (at release or 28 days). For example, the UHPC beams had shorter transfer lengths that the NSC or NSS beams.

To determine development length, each beam end was tested in flexure using a concentrated point load located at a predetermined distance from the beam end. This is shown in Fig. 7. The failure mode for each beam was investigated and used to determine development length. The typical failure modes observed were flexure, strand slip then flexure, and shear cracking then strand slip. This procedure has been used by others researchers [1, 4-6, 8, 10, 12, 20, 26].

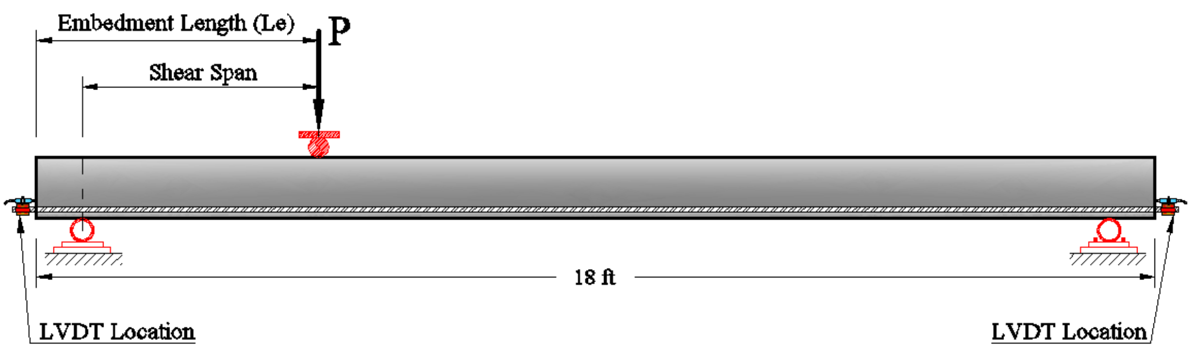


Fig. 7 Development length test set-up for all trial beams

LVTDs with an accuracy of 0.01 in. (0.25mm) were attached to each strand at the end of the beam. Readings from the LVTDs were continuously recorded and monitored using the data acquisition system in order to determine strand slip [12, 19, 20]. If the beam did not exhibit strand slip at failure and a pure flexural failure was recorded, a shorter embedment length was used for the next test. However, if strand slip was observed before than the nominal moment capacity was achieved, a bond failure was recorded and a longer embedment length was used for the next test. As a result, the development length was considered to be the embedment length where the bond and flexural failures occurred at the same time while achieving the nominal moment for the specimen [1, 7, 10, 27-29].

VARIABLES CONSIDERED IN THE ANALYSIS

For this research program, several variables were examined in order to determine the magnitude of their effect on transfer and development length. These variables include concrete compressive strength at prestress release (f'_{ci}) and at the time of testing (f'_c), initial prestress in the strand (f_{si}), effective prestress in the strand after all losses (f_{se}), stress in the strand at nominal strength (f_{ps}), and nominal strand diameter (d_b). Although, these variables are essential for transfer and development lengths, there are other variables which can be considered important in the analysis such as friction between strands and concrete, type of release, strand surface condition, confining reinforcement around strand, and type of loading [1, 8, 10, 26, 27, 30].

TRANSFER LENGTH ANALYSIS

Transfer length data were plotted in Fig. 5 and Fig. 6. These figures show the decrease in transfer length that occurs as concrete compressive strength increases. A power regression analysis was used to analyze this data although several researchers have used a linear regression analysis. The minimum, average, and maximum transfer length at release and 28-days for all beams are presented in Table 4. Table 4 also contains the average concrete compressive strength at release day (f'_{ci}) and 28-day (f'_{c}), the average of the effective strand stress after all losses (f_{se}), and the predicted transfer length using the ACI & AASHTO code equations (Equations 3 and 4). For all beams, the maximum measured transfer length is for the series NSS, which also has the lowest compressive strength at release. For one of the NSS beams, the measured was about 37.5% more than the predicted value, while the average transfer length for the same series was approximately 92.44% of the predicted value. On the other hand, the predicted transfer length for the UHPC beams is about 200% or more than the measured values.

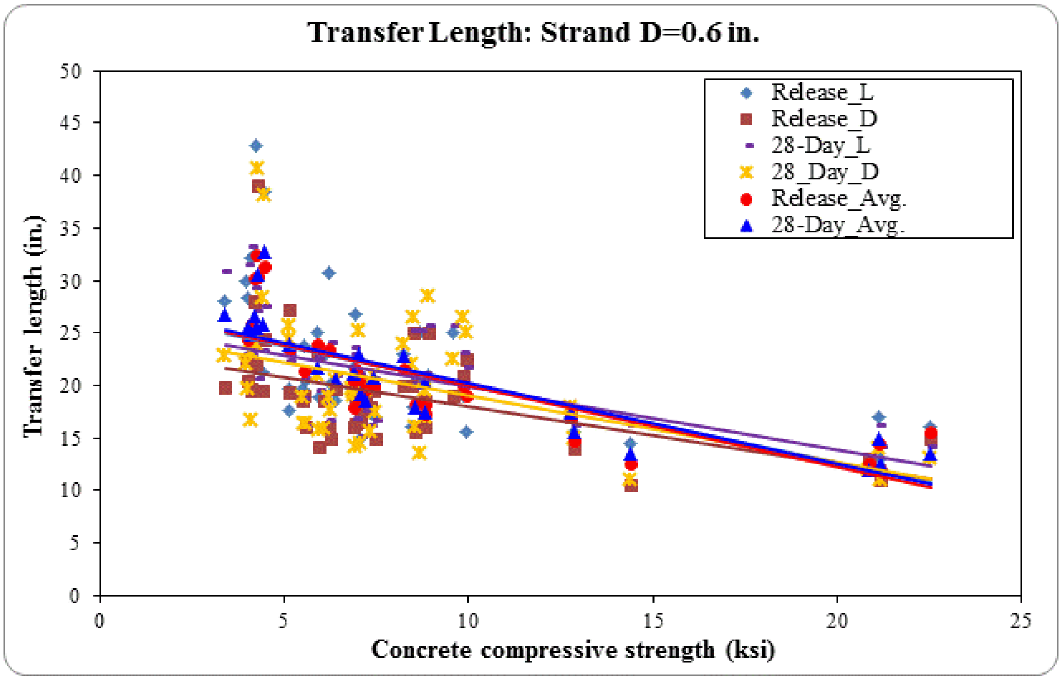
Table 4 Measured and predicted transfer length

Series	f'_{ci} *(ksi)*	f'_{c} *(ksi)*	f_{se} *(ksi)*	**Reported Transfer Lengths (in.): Release**			**Reported Transfer Lengths (in.): 28-Day**			**ACI & AASHTO**
				Min.	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Predicted**
NSS	4.05	6.12	156.0	19.9	28.8	42.9	22.0	26.8	38.2	31.2
NSCL	4.42	5.69	155.1	19.5	23.5	32.1	16.7	25.0	33.1	31.0
NSL	4.75	7.59	169.1	17.7	21.9	39.0	18.5	24.0	40.6	33.8
HSS	6.03	7.02	166.1	16.1	20.5	26.8	14.2	16.8	20.5	33.2
HSCL	6.21	7.12	167.4	14.2	19.2	30.7	15.7	19.2	24.0	33.5
HSL	6.91	9.25	176.2	18.1	19.8	21.7	19.3	20.9	25.2	35.2
SCCIII	7.35	11.04	176.3	15.0	18.0	23.0	14.5	19.0	24.0	35.3
SCCI	7.76	12.24	180.5	15.5	20.0	25.0	13.5	20.2	26.5	36.1
HSC	9.32	12.39	182.2	15.5	19.9	25.0	17.0	22.8	28.5	36.4
UHPC	17.96	26.39	188.1	10.5	14.1	17.0	11.0	14.2	18.0	37.6
LWSCC (*)	4.56	6.66	172.0	15.0	20.7	33.0	13.0	20.1	27.0	28.7

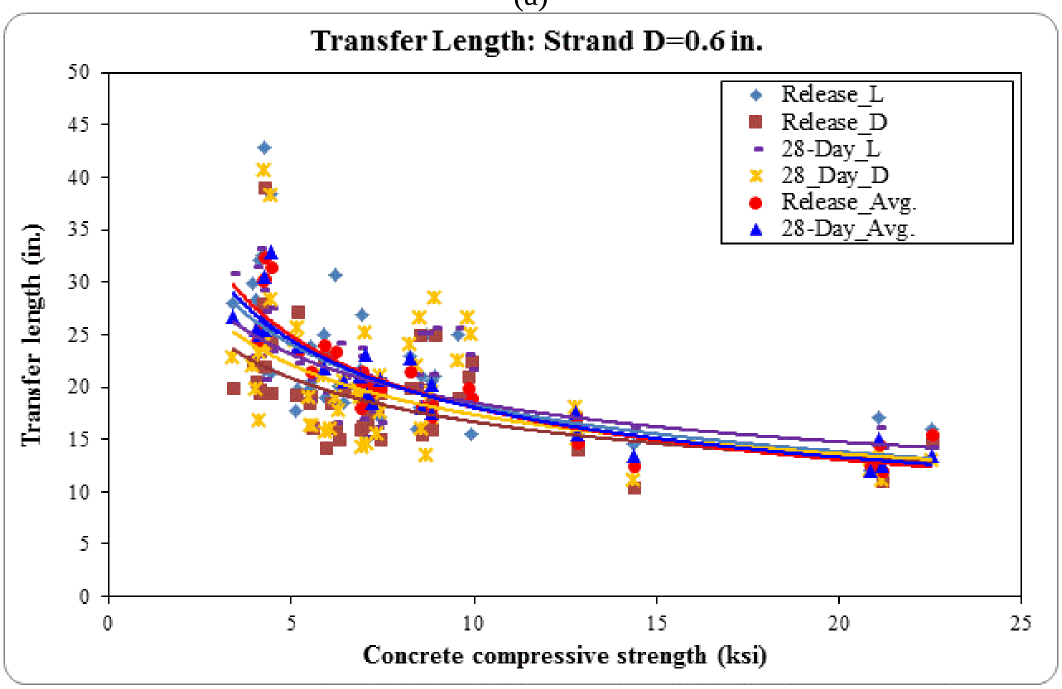
(*): Strand 0.5-in. diameter was used in this case

Note: 1 in. = 25.4 mm, 1 psi = 0.006895 MPa, 1 ksi = 6.895 MPa.

Fig. 8 shows two types of statistical analysis such as linear regression and power regression performed on the data. A power regression analysis was chosen due to the fact this analysis presented an efficient regression. The measured transfer lengths at both ends of all beams, dead end and live end, at release and 28 days of age versus concrete compressive strengths (f'_{ci}) at release are shown in Fig. 8b.



(a)



(b)

Fig. 8 Transfer length analysis: (a) linear regression and (b) power regression

The average, measured transfer length for each series of beams at release and at 28 days of age is shown in Table 5. Table 5 also shows the calculated transfer lengths using prediction equations from ACI 318-11 (section 12.9) and AASHTO LRFD, ACI 318-11 (section 11.3.4 and 11.3.5, $L_t = 50d_b$), and AASHTO LRFD (Article 5.11.4.1, $L_t = 60d_b$). Fig. 9 shows that both ACI and AASHTO overestimate transfer length at release and at 28 days of age.

Table 5 Transfer lengths at release and 28 days for all series of beams

Series	***f_{se}* (ksi)**	**Transfer Lengths (in.)**					**Ratio: Measured/ACI & AASHTO**	
		Measured Transfer Lengths (in.)		**ACI & AASHTO**	**ACI**	**AASHTO**		
		Release	**28 - Day**	**$f_{se}d_b/3$**	**$50d_b$**	**$60d_b$**	**Release**	**28 - Day**
NSS	156.0	28.8	26.8	31.2	30	36	0.92	0.86
NSCL	155.1	23.5	25.0	31.0	30	36	0.76	0.81
NSL	169.1	21.9	24.0	33.8	30	36	0.65	0.71
HSS	166.1	20.5	16.8	33.2	30	36	0.62	0.50
HSCL	167.4	19.2	19.2	33.5	30	36	0.57	0.57
HSL	176.2	19.8	20.9	35.2	30	36	0.56	0.59
SCCIII	176.3	18.0	19.0	35.3	30	36	0.51	0.54
SCCI	180.5	20.0	20.2	36.1	30	36	0.55	0.56
HSC	182.2	19.9	22.8	36.4	30	36	0.55	0.63
UHPC	188.1	14.1	14.2	37.6	30	36	0.38	0.38
LWSCC (*)	172.0	20.7	20.1	28.7	25	30	0.72	0.70

(*): Strand 0.5-in. diameter was used in this case
Note: 1 in. = 25.4 mm, 1 psi = 0.006895 MPa, 1 ksi = 6.895 MPa.

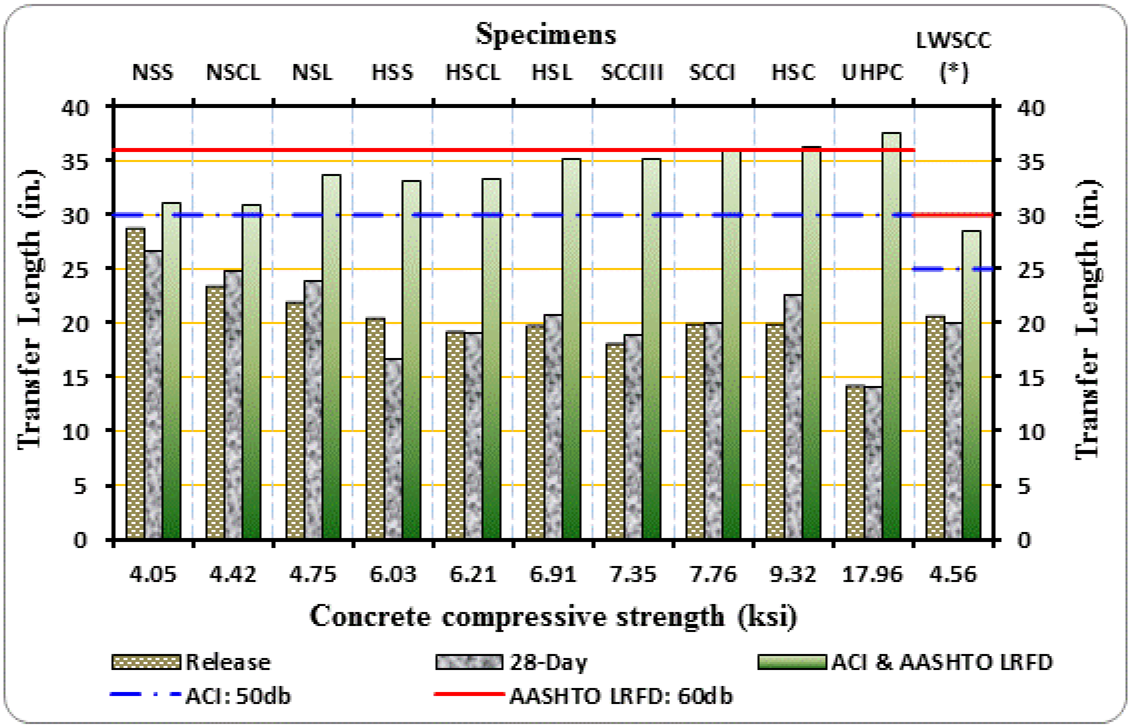


Fig. 9 Analysis of transfer length for different specimens

As previously determined by other investigators [5, 10, 12, 20], transfer length decreased as concrete compressive strength increased. This infers that concrete compressive strength at release and at 28 days of age is an important variable that should be included in transfer length equations. Other variables included initial prestress (f_{si}), strand diameter (d_b), and the effective strand stress after all losses (f_{se}). Several analyses have been performed using these variables (Fig. 10). The transfer length equations obtained are shown below.

$$L_t = 6.0\left(\frac{f_{si}}{f'_{ci}} d_b\right)^{0.55} \tag{5}$$

$$L_t = 6.0\left(\frac{f_{se}}{f'_{ci}} d_b\right)^{0.55} \tag{6}$$

where:
L_t = transfer length (in.)
f'_{ci} = concrete compressive strength at release (ksi)
f_{si} = initial prestress (ksi)
f_{se} = effective prestressing stress after all losses (ksi)
d_b = strand diameter (in.)

Eq. (5) and Eq. (6) were called as proposed equations Lt1 and Lt2 respectively, and these can be seen in Fig. 10.

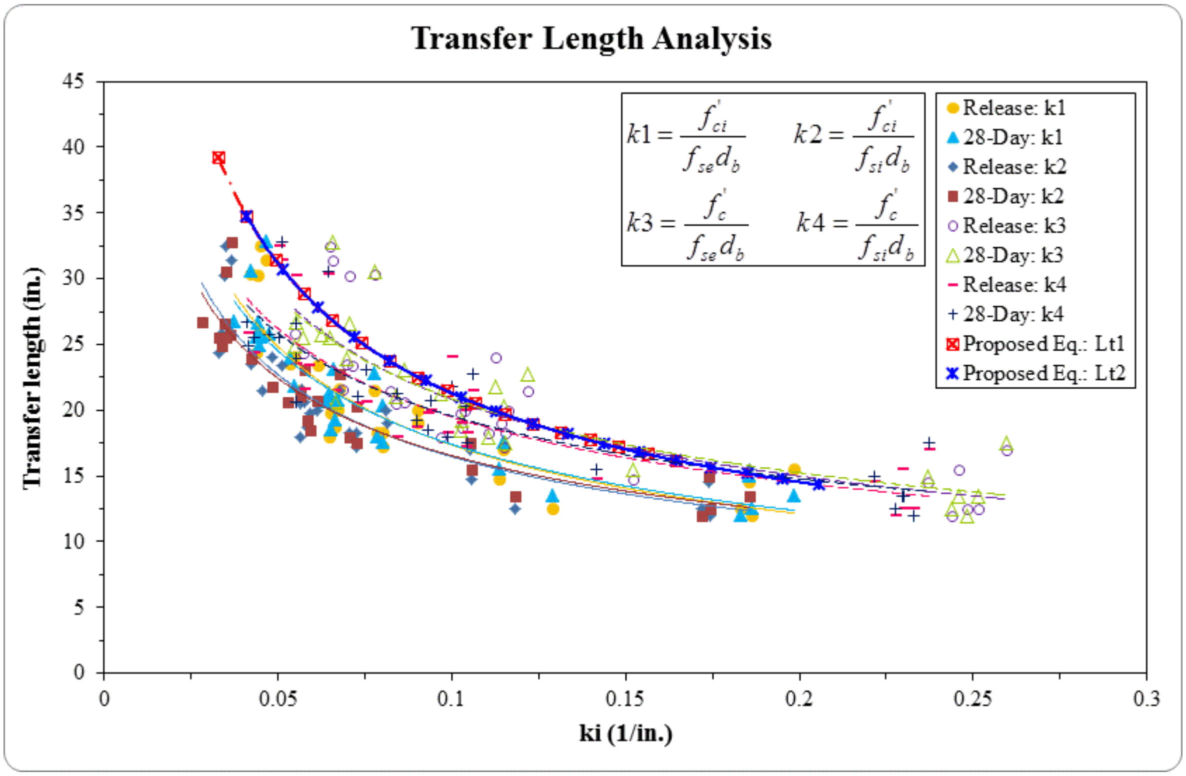


Fig. 10 Analysis of transfer length by using different considerations

Both proposed equations look similar due to the fact during the statistical analysis the variables produced similar coefficients. Thus, in order to make a comparison analysis between the two proposed equations and the ACI 318 Building Code and AASHTO LRFD equations, the coefficients in both cases were assumed to be the same. Table 6 presents measured transfer length at release and 28 days for each series as well as the transfer lengths calculated using ACI and AASHTO LRFD and proposed equations (Lt1 and Lt2).

Fig. 11 shows that the first proposed equation, Lt1, presented values greater than measured. For release strengths less than 5 ksi, Lt1 predicted transfer lengths greater that the ACI & AASHTO, ACI (50d_b), AASHTO LRFD (60d_b) equations. For release strengths greater than 5 ksi, Lt1 was more accurate than the ACI & AASHTO equations and the 60d_b equation. When compared to all ACI & AASHTO equations, the second proposed equation Lt2 predicted transfer length values that were also closer to the measured values for concrete specimens with compressive strengths greater than 5 ksi at release. At release strengths greater than 5 ksi, Lt2 predicted transfer lengths that were more similar to the measured values than those predicted by Lt1.

Table 6 Comparison of different transfer lengths with proposed equations (Lt1 and Lt2)

Series	***f'***		**Transfer Lengths (in.)**				
			Measured Transfer Lengths (in.)		**ACI & AASHTO**	**Proposed Equation**	
	***f'_{ci}* (ksi)**	***f_{se}* (ksi)**	**Release**	**28-Day**	**$f_{se}d_b/3$**	**Lt1**	**Lt2**
NSS	4.05	156.0	28.8	26.8	31.2	39.0	33.7
NSCL	4.42	155.1	23.5	25.0	31.0	37.1	32.0
NSL	4.75	169.1	21.9	24.0	33.8	35.7	32.3
HSS	6.03	166.1	20.5	16.8	33.2	31.3	28.1
HSCL	6.21	167.4	19.2	19.2	33.5	30.8	27.7
HSL	6.91	176.2	19.8	20.9	35.2	29.0	26.9
SCCIII	7.35	176.3	18.0	19.0	35.3	28.1	26.0
SCCI	7.76	180.5	20.0	20.2	36.1	27.2	25.6
HSC	9.32	182.2	19.9	22.8	36.4	24.6	23.2
UHPC	17.96	188.1	14.1	14.2	37.6	17.2	16.5
LWSCC (*)	4.56	172.0	20.7	20.1	28.7	33.0	30.2

(*): Strand 0.5-in. diameter was used in this case

From this analysis of transfer length one can see that the transfer length decreases if the concrete compressive strength at release is greater than 7.0 ksi. Although these values are less than ACI 318 Building Code and AASHTO LRFD, the transfer length for beams cast with concrete with a compressive strength less than 7.0 ksi is greater or similar to ACI and AASHTO equations.

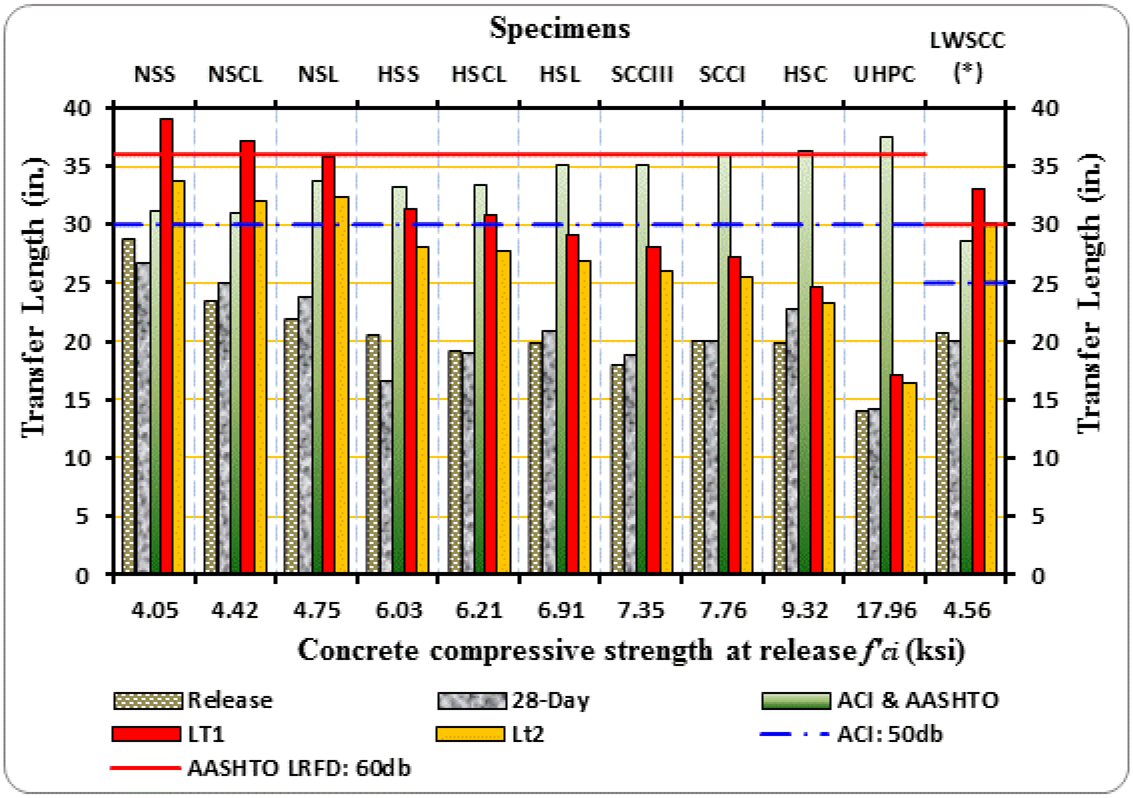


Fig. 11 Relationship of the concrete compressive strength and the transfer length

DEVELOPMENT LENGTH ANALYSIS

The results of development length testing for each series are summarized in Table 7. In each set of specimens, at least one beam exhibited strand slip before achieving the nominal moment capacity (M_n). At least one failed without strand slip occurring. The development length would be the embedment when the moment that slip occurred (M_{slip}) was equal to the nominal moment capacity (M_n), although shear failures at short embedment lengths made determining development somewhat difficult to measure [12, 19, 20].

Table 7 Measured development length results

Series	***L_E* *(in.)***	***f'_c* *(ksi)***	***f_{se}* *(ksi)***	***f_{ps}* *(ksi)***	***M_n* *(k-in.)***	***M_{max}* *(k-in.)***	***M_{slip}* *(k-in.)***	$\frac{M_{max}}{M_n}$	$\frac{M_{slip}}{M_n}$
NSCL	51	5.69	155.1	260.7	952.8	968.0	824.8	1.02	0.87
NSS	45	6.12	156.0	261.3	960.6	970.0	911.6	1.01	0.95
HSS	41	7.02	166.1	262.5	979.0	1008.1	864.9	1.03	0.88
HSCL	44	7.12	167.4	262.6	981.8	1016.0	909.5	1.03	0.93
NSL	42	7.59	169.1	262.7	989.3	1049.6	796.0	1.06	0.80
HSL	43	9.25	176.2	264.0	1016.3	1065.0	985.6	1.05	0.97
SCCIII	33	11.04	176.3	265.8	1058.0	1212.4	1109.3	1.15	1.05
SCCI	38	12.24	180.5	266.1	1066.9	1246.6	1032.5	1.17	0.97
HSC	36	12.39	182.2	266.0	1064.8	1288.2	1089.7	1.21	1.02
UHPC	34	26.39	188.1	267.7	1504.4	1757.5	1750.3	1.17	1.16
LWSCC (*)	32	6.66	172.0	265.3	753.6	848.2	731.3	1.13	0.97

(*): Strand 0.5-in. diameter was used in this case

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, 1 in. = 25.4 mm, 1 kip-in. = 0.1130 kN-m.

Using the same idea for the transfer length analysis, the flexural bond length analysis was performed in order to obtain a development length equation [1, 31]. The flexural bond length analysis is likely complicated because not all of the embedment length data can be considered in the analysis. This is due to the nature of the testing and their results. The testing protocol identified a range of embedment lengths in which the development length was likely to fall between two values. Variables considered in the analysis included concrete compressive strength at 28 days (f'_c), effective strand stress after all losses (f_{se}), stress in the strand at nominal flexural strength (f_{ps}), and strand diameter (d_b). Through the statistical analysis, power regression analysis, two flexural bond lengths equations were obtained with different considerations. The first equation differs from the second by one variable which is the concrete compressive strength at 28 days (f'_c). The two equations are shown below as Eqs. (7) and (8).

$$L_b = 15.5\left(\frac{f_{ps} - f_{se}}{f'_c} d_b\right)^{0.55} \tag{7}$$

$$L_b = 0.001\left[(f_{ps} - f_{se})d_b\right]^{2.6} \tag{8}$$

Having transfer length and flexural bond length, the development length will be a sum of both lengths. Then, these equations of development length are given by

$$L_d = 6.0\left(\frac{f_{si}}{f_{ci}^{'}} d_b\right)^{0.55} + 15.5\left(\frac{f_{ps} - f_{se}}{f_c^{'}} d_b\right)^{0.55} \quad (9)$$

$$L_d = 6.0\left(\frac{f_{se}}{f_{ci}^{'}} d_b\right)^{0.55} + 0.001\left[(f_{ps} - f_{se}) d_b\right]^{2.6} \quad (10)$$

where:
L_d = development length (in.)
f'_{ci} = concrete compressive strength at release (ksi)
f'_c = design concrete compressive strength (ksi)
f_{si} = initial prestress (ksi)
f_{se} = effective prestressing stress after all losses (ksi)
f_{ps} = stress in the strand at nominal flexural strength (ksi)
d_b = strand diameter (in.)

Eq. (9) was named as proposed equation Ld1 while Eq. (10) was called as proposed equation Ld2. These expressions are written and shown in Table 8 and in Fig. 12, which presents comparisons of embedment length and ACI 318 Building Code and AASHTO LRFD (different considerations), and proposed equations. The flexural bond length equation used for the ACI 318 Building Code and AASHTO LRFD is written in Eq. (2). From this analysis, the values of proposed equations, ACI 318 Building Code, and AASHTO LRFD are greater than measured embedment lengths. Although the first proposed equation is greater than the ACI & AASHTO LRFD values for series NSCL and NSS (concrete compressive strength less than 7.0 ksi), these values are less than AASHTO LRFD ($60d_b + L_b$). However, when the concrete compressive strength is greater than 7.0 ksi, the development length obtained using the proposed equations began to decrease compared to the ACI Code and AASHTO LRFD equations. Researchers have affirmed that the development length determined by the ACI Code and AASHTO LRFD equations is very conservative, which are confirmed in this analysis, however some researchers have said the opposite [5, 6, 8, 26].

Table 8 Comparisons of calculated versus measured L_d and proposed equations

Series	L_E (in.)	f'_c (ksi)	f_{se} (ksi)	f_{ps} (ksi)	Development Lengths (in.)				
					ACI & AASHTO	ACI	AASHTO LRFD	Proposed Equations	
					$f_{se}d_b/3 + L_b$	$50d_b + L_b$	$60d_b + L_b$	Ld1	Ld2
NSCL	51	5.69	155.1	260.7	94.4	93.4	99.4	95.5	80.5
NSS	45	6.12	156.0	261.3	94.4	93.2	99.2	94.9	81.8
HSS	41	7.02	166.1	262.5	91.0	87.8	93.8	80.7	66.2
HSCL	44	7.12	167.4	262.6	90.6	87.2	93.2	79.5	64.7
NSL	42	7.59	169.1	262.7	90.0	86.2	92.2	82.3	67.7
HSL	43	9.25	176.2	264.0	87.9	82.7	88.7	69.4	56.8
SCCIII	33	11.04	176.3	265.8	88.9	83.7	89.7	65.1	57.4
SCCI	38	12.24	180.5	266.1	87.5	81.4	87.4	61.3	53.6
HSC	36	12.39	182.2	266.0	86.7	80.3	86.3	58.1	49.8
UHPC	34	26.39	188.1	267.7	85.4	77.8	83.8	38.7	39.7
LWSCC (*)	32	6.66	172.0	265.3	75.3	71.6	76.6	78.2	52.0

(*): Strand 0.5-in. diameter was used in this case

Note: L_E = embedment length, 1 in. = 25.4 mm, 1 kip-in. = 0.1130 kN-m.

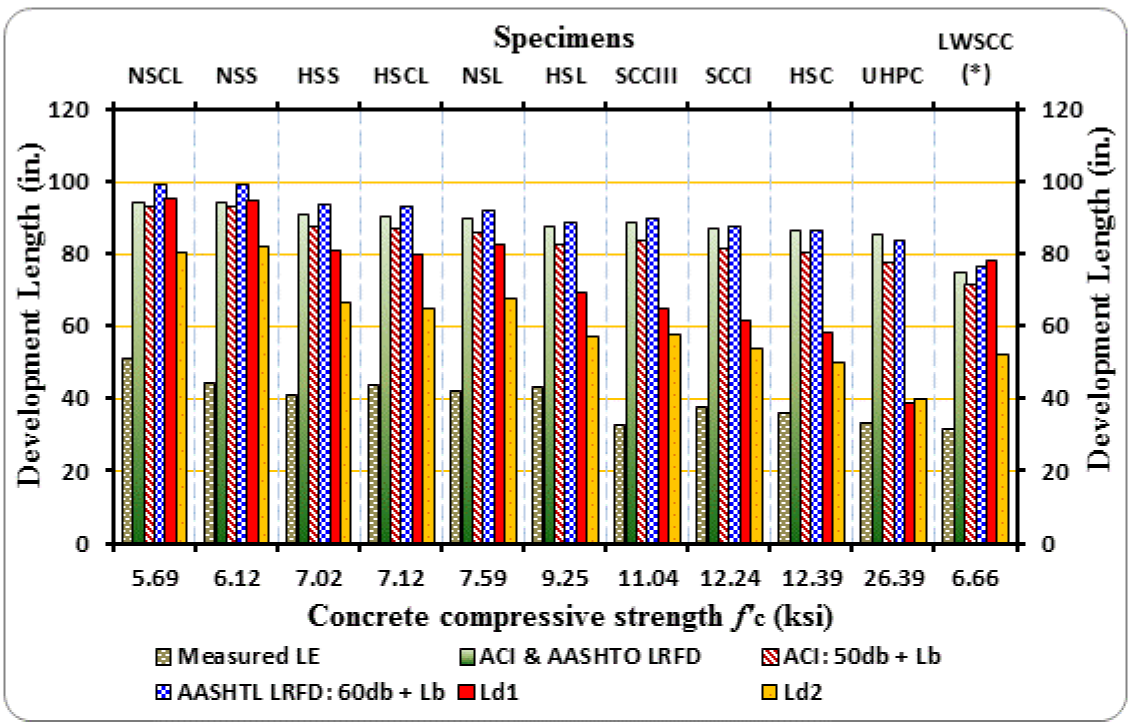


Fig. 12 Comparison of development lengths

COMPARISON TO NCHRP 603

Ramirez and Russell, 2008, conducted an investigation through the National Cooperative Highway Research Program (NCHRP 603) Project 12-60 [10]. Under this project the transfer and development lengths on prestressed concrete were studied in 43 rectangular-shaped beams and 8 I-shaped beams cast high-strength, normal weight concrete. They examined concrete mixtures which had compressive strengths of up to 15 ksi at testing. The concrete compressive strengths measured at release were between 4 ksi and 10 ksi. The research showed that increasing concrete strength presented a clear correlation between shortening of transfer and development lengths for both strands 0.5 and 0.6 in. As a result, Eq. 11 was recommended to be included into Article 5.11.4.2 of the *AASHTO LRFD Bridge Design Specifications*. The particular of this new equation was that the concrete compressive strength at release (f'_{ci}) was included in.

In Eq. 11, a beam which has a release strength of 4 ksi has a transfer length of 60 strand diameters ($60d_b$). This is the same value provided by AASHTO LRFD Article 5.11.4.1. The researchers also recommended that for concrete release strengths greater than 9 ksi, the transfer length will be no less than 40 strand diameters ($40d_b$).

$$L_t = \left(\frac{120 d_b}{\sqrt{f'_{ci}}} \right) \leq 40 d_b \tag{11}$$

where:
Lt = transfer length (in.)
f'_{ci} = concrete compressive strength at release (ksi)
d_b = strand diameter (in.)

Eq. 12, an expression of development length proposed by Ramirez and Russell, provides a development length of about 150 strand diameters ($150d_b$) for normal concrete with release strength of 4 ksi and design strength of 6 ksi. According to this expression, the development length cannot be less than 100 strand diameters ($100d_b$) for high-strength concrete [10]..

$$L_d = \left(\frac{120}{\sqrt{f'_{ci}}} + \frac{225}{\sqrt{f'_c}} \right) d_b \geq 100 d_b \tag{12}$$

where:
Lt = transfer length (in.)
f'_{ci} = concrete compressive strength at release (ksi)
f'_c = design concrete compressive strength (ksi)
d_b = strand diameter (in.)

Fig. 13 shows how the transfer lengths due to proposed equations (Lt1 and Lt2) decrease when the concrete compressive strength at release increased from 4.0 ksi to 20.0 ksi. The values of the initial prestress and the effective strand stress after all losses were 202.5 ksi and 162 ksi, respectively. These values were considered as a constant for each concrete compressive strength at release. The strand diameter used was 0.6 in. The transfer lengths shown in Fig. 13 are less than $40d_b$ (40 x 0.6 = 24 in.) which is the minimum value of transfer length for concrete compressive strength over 9 ksi.

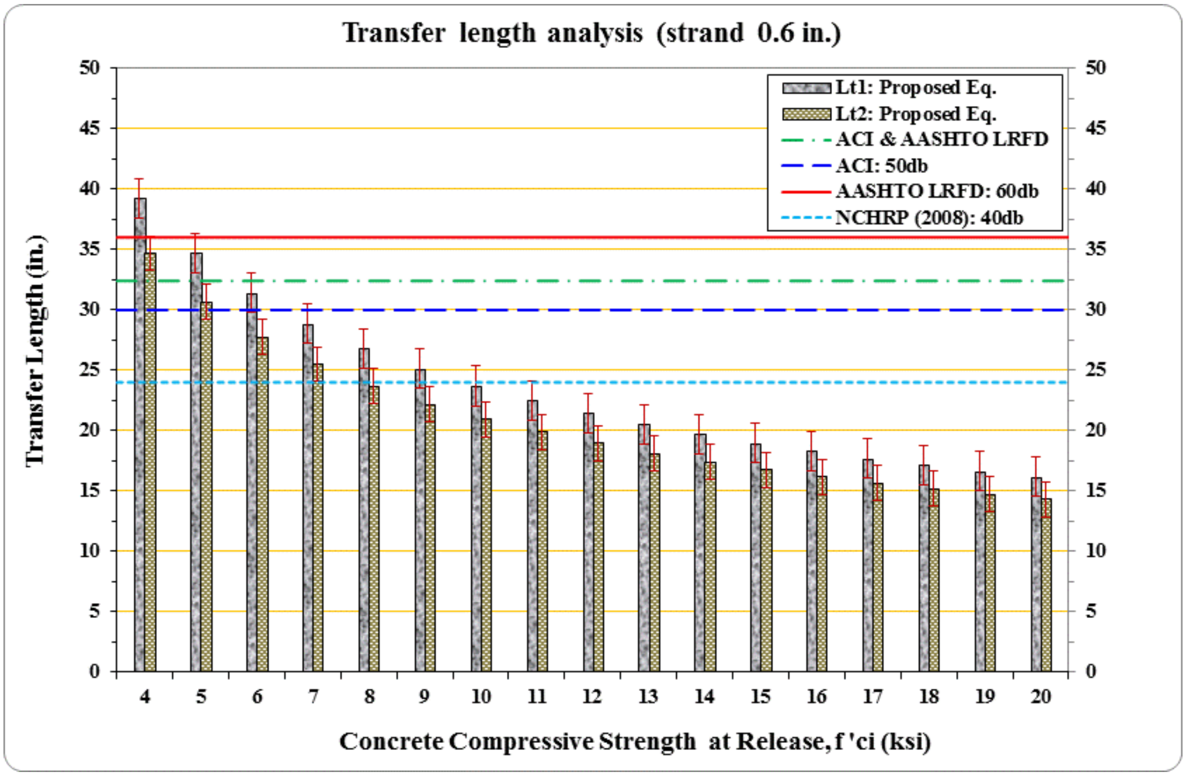


Fig. 13 Transfer length for different concrete compressive strength at release

From this analysis of transfer length one can see that the transfer length begins to decrease if the concrete compressive strength at release is greater than 7.0 ksi. Although these values are less than the ACI Code and AASHTO LRFD, the transfer length for the concrete compressive strength less than 7.0 ksi is greater or similar to that predicted by the ACI Code and AASHTO LRFD.

Fig. 14 shows a comparison of development lengths where the minimum development length ($100d_b$) value was included in the analysis [10]. For a strand diameter equal to 0.6 in., the minimum development length is 60 in. (100x0.6 = 60 in.). All development lengths measured were less than values of development lengths calculated using 100db, the ACI and AASHTO LRFD equations, and the proposed equations (Ld2 and Ld2). Ld1 values are greater than $100d_b$ values for design concrete strength between 5 ksi and 12 ksi, but over the 12 ksi the values due to Ld1 are less than the minimum value of development length ($100d_b$). On the other hand, Ld2 results were less than $100d_b$ values for design concrete strength over 9 ksi, which was the same value recommended by Ramirez and Russell (2008) [10].

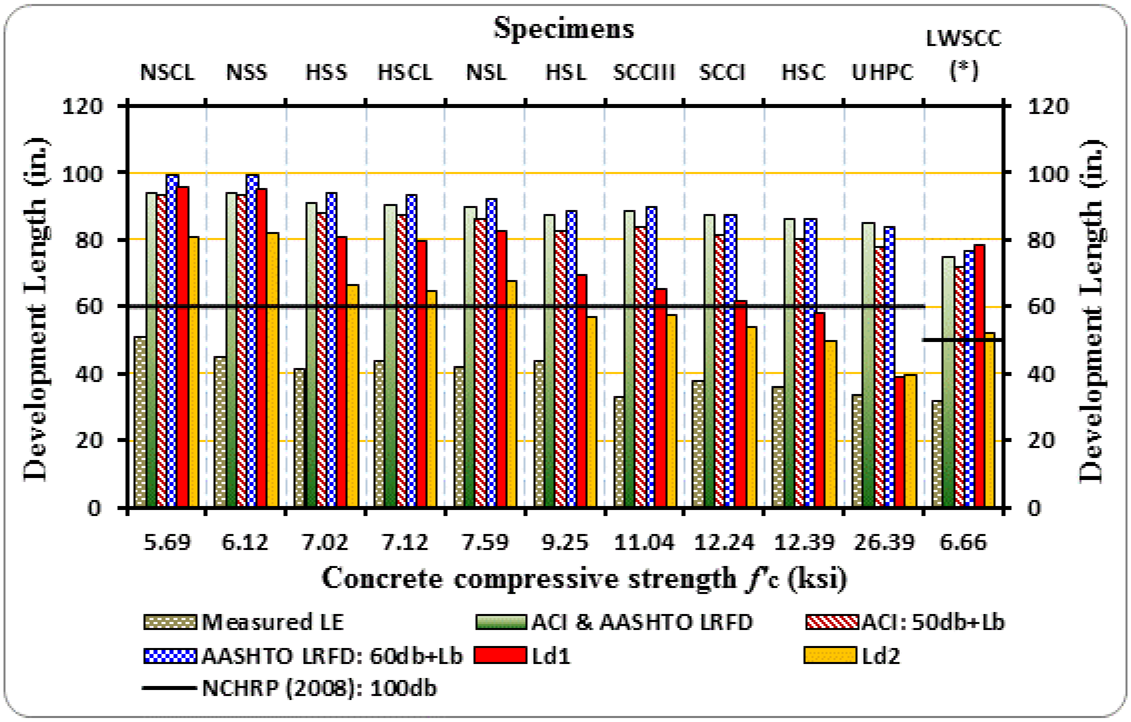


Fig. 14 Development length for different design concrete compressive strength

CONCLUSIONS

The principal goal of this paper is to show how concrete compressive strength plays an important role in transfer and development length. The importance of this parameter has also been reported by other researchers whether or not it should be included into the ACI 318 Building Code and AASHTO LRFD, which never considered it.

The results showed that transfer lengths were larger in magnitude when the compressive strength at release was less than 5000 psi. However, when the compressive strength at release was greater than 5000 psi, there was little difference in transfer length.

When comparing the measured transfer lengths to the predicted transfer length, specimen size must be considered. Russell and Burns (1993) examined the relationship between the transfer and development lengths of AASHTO type specimens and small rectangular prisms used in the past and current research. According their research, the AASHTO type specimens demonstrated significantly shorter transfer lengths than the smaller testing beam sizes [17]. Therefore the results of the UA project are also conservative when compared to values that would be obtained using larger specimens.

Similar trends were apparent in the development length results at compressive strengths greater than 7000 psi. The transfer length and development lengths decrease when the concrete compressive strength at release and 28-day increase. Greater compressive strengths help dissipate energy from the strand, which means these beams will require less development length than beams with normal strength concrete.

REFERENCES

[1] Hanson, N. W., and Kaar, P. H., 1959, "Flexural bond tests of pretensioned prestressed beams," ACI Structural Journal, 55(1), pp. 783-802.
[2] ACI, 2011, Building code requirements for structural concrete and commentary (ACI 318-11), American Concrete Institute, Farmington Hills, MI.
[3] AASHTO, 2012, AASHTO LRFD Bridge Design Specifications, Customary U.S. Units (6^{th} ed.), American Association of State and Highway Transportation Officials Washington, D.C.
[4] Buckner, C. D., March-April 1995, "A review of strand development length for pretensioned concrete members," PCI Journal, 40(2), pp. 84-105.
[5] Mitchell, D., Cook, W. D., Khan, A. A., and Tham, T., May-June 1993, "Influence of high strength concrete on transfer and development length of pretensioning strand," PCI Journal, 38(3), pp. 52-66.
[6] Deatherage, J. H., Burdette, E. G., and Chew, C. K., January-February 1994, "Development length and lateral spacing requirements of prestressing strands for prestressed concrete bridge girders," PCI Journal, 39(1), pp. 70-83.
[7] Kose, M. M., and Burkett, W. R., September-October 2005, "Formulation of new development length equation for 0.6 in. prestressing strand," PCI Journal, 50(5), pp. 96-105.
[8] Zia, P., and Mostafa, T., September-October 1977, "Development length of prestressing strands," PCI Journal, 22(5), pp. 54-65.
[9] Cousins, T. E., and Nassar, A., 2003, "Investigation of transfer length, flexural strength, and prestress losses in lightweight prestressed concrete girders " No. FHWA/VTRC 03-CR20, Virginia Department of Transportation, Charlottesville, VA.
[10] Ramirez, J. A., and Russell, B. W., 2008, Transfer, Development, and Splice Length for Strand/Reinforcement in High-Strength Concrete, Transportation Research Board, National Research Council, Washington, D.C.
[11] Martí-Vargas, J. R., Serna, P., Navarro-Gregori, J., and Bonet, J. L., 2012, "Effects of concrete composition on transmission length of prestressing strands," Construction and Building Materials, 27(1), pp. 350-356.
[12] Floyd, R. W., Ruiz, E., D., Do, N. H., Staton, B. W., and Hale, W. M., 2011, "Development lengths of high-strength self-consolidating concrete beams," PCI Journal, 56(1), pp. 36-53.
[13] Floyd, R. W., 2012, "Investigating the bond of prestressing strands in lightweight self-consolidating concrete," 3517274 Ph.D., University of Arkansas, United States - Arkansas.
[14] Ruiz Coello, E. D., 2007, "Prestress losses and development length in pretensioned ultra high performance concrete beams," 3276882 Ph.D., University of Arkansas, United States -- Arkansas.
[15] Staton, B. W., 2006, "Transfer lengths for prestressed concrete beams cast with self-consolidating concrete mixtures," 1445636 M.S.C.E., University of Arkansas, United States -- Arkansas.

[16] Ward, D., 2010, "Performance of prestressed double-tee beams cast with lightweight self-consolidating concrete," 1484691 M.S.C.E., University of Arkansas, United States -- Arkansas.
[17] Russell, B. W., and Burns, N. H., 1993, "Design guidelines for transfer, development and debonding of large diameter seven wire strands in pretensioned concrete girders (Report No 1210-5F).", Texas State Department of Highways and Public Transportation.
[18] Do, N. H., Staton, B. W., and Hale, W. M., "Development of high strength self-consolidating concrete mixtures for use in prestressed bridge girders," Proc. The PCI National Bridge Conference, CD-ROM.
[19] Floyd, R. W., Howland, M. B., and Micah Hale, W., 2011, "Evaluation of strand bond equations for prestressed members cast with self-consolidating concrete," Engineering Structures, 33(10), pp. 2879-2887.
[20] John, E. E., Ruiz, E. D., Floyd, R. W., and Hale, W. M., 2011, "Transfer and Development Lengths and Prestress Losses in Ultra-High-Performance Concrete Beams," Transportation Research Record: Journal of the Transportation Research Board, 2251, pp. 76-81.
[21] Staton, B. W., Do, N. H., Ruiz, E. D., and Hale, W. M., 2009, "Transfer lengths of prestressed bemas cast with self-consolidating concrete," PCI Journal, 54(2), pp. 64-83.
[22] Girgis, A. F. M., and Tuan, C. Y., November-December 2005, "Bond strength and transfer length of pretensioned bridge girders cast with self-consolidating concrete," PCI Journal, 50(6), pp. 72-87.
[23] Oh, B. H., and Kim, E. S., 2000, "Realistic evaluation of transfer lengths in pretensioned, prestressed concrete members," ACI Structural Journal, 97(6), pp. 821-830.
[24] Russell, B. W., and Burns, N. H., September-October 1996, "Measured transfer lengths of 0.5 and 0.6 in. strands in pretensioned concrete," PCI Journal, 41(5), pp. 44-65.
[25] Russell, B. W., and Burns, N. H., 1997, "Measured of transfer lengths of pretensioned concrete elements," Journal of Structural Engineering, 123(5), pp. 541-549.
[26] Cousins, T. E., Johnston, D. W., and Zia, P., July-August 1990, "Transfer and development length of epoxy coated and uncoated prestressing strand," PCI Journal, 35(4), pp. 92-103.
[27] Kim, Y. H., Trejo, D., and Hueste, M. B. D., 2012, "Bond performance in self-consolidating concrete pretensioned bridge girders," ACI Structural Journal, 109(6), pp. 755-766.
[28] Lane, S. N., 1998, "A new development length equation for pretensioned strands in bridge beams and piles," No. FHWA-RD-98-116,Final Report,3D1a, Federal Highway Administration, Turner-Fairbank Highway Research Center, 6300 Georgetown Pike, McLean, VA 22101 USA.
[29] Park, H., Din, Z. U., and Cho, J.-Y., 2012, "Methodological Aspects in measurement of strand transfer length in pretensioned concrete," ACI Structural Journal, 109(5), pp. 625-634.
[30] Rose, D. R., and Russell, B. W., July-August 1997, "Investigation of standardized tests to measure the bond performance of prestressing strand," PCI Journal, 42(4), pp. 56-80.
[31] Mahmoud, Z. I., Rizkalla, S. H., and Zaghloul, E.-E. R., 1999, "Transfer and development lengths of carbon fiber reinforced polymers prestressing reinforcement," ACI Structural Journal, 96(4), pp. 594-602.