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Effect of concrete compressive strength on transfer length

Alberto T. Ramirez-Garcia [a], Royce W. Floyd [b], W. Micah Hale [a,*], J.R. Martí-Vargas [c]

[a] Department of Civil Engineering, 4190 Bell, University of Arkansas, Fayetteville, AR 72701, United States
[b] School of Civil Engineering and Environmental Science, 202 W. Boyd St. Room 334, Norman, OK 73019, United States
[c] Universitat Politècnica de València (UPV), València, Spain

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ABSTRACT

This paper examines the effect of concrete compressive strength on the transfer length of prestressing strands. The paper includes the results from several research projects conducted at the University of Arkansas (UA) and from testing reported in the literature. At the UA, 57 prestressed, precast beams have been cast since 2005. The beams were cast with selfconsolidating concrete (SCC), high strength concrete (HSC), lightweight self-consolidating concrete (LWSCC), and ultra-high performance concrete (UHPC). Using data from the UA and from the literature, an equation to estimate transfer length was developed and presented. The results were also compared with the American Concrete Institute (ACI 318) and the American Association of State Highway and Transportation Officials (AASHTO) prediction equations for transfer length, which were designed for conventional concrete. The results also showed that there was little change in transfer length when the compressive strength at release was greater than 34.5 MPa.

1. Introduction

Prestressed concrete has been used extensively since the 1950s. Many buildings and bridge structures utilize its principles, especially pre-cast structures. In the design of pretensioned members, there is a particular focus on the length a strand must be embedded in the concrete in order to develop its bond strength. Transfer length refers to the strand length required to transfer the initial prestress in the strand to the concrete.

The ACI 318 Building Code and Commentary (hereafter referred to as ACI 318-14) [1] and the AASHTO Load and Resistance Factor Design (LRFD) [2] Specifications (hereafter referred to as AASHTO) provide equations to estimate transfer length. The equation is a function of the effective prestress (f_{se}) and the strand diameter (d_b) [1–3]. Investigators have shown that initial prestress (f_{si}), and concrete compressive strength both at prestress release (f'_{ci}) and at 28-days (f'_c), contribute to transfer length [3–8].

With the changes occurring regarding concrete mixture proportioning and properties, researchers have and are questioning the accuracy of the ACI 318-14 and AASHTO equations. In these design codes, concrete compressive strength is not a variable in the transfer length equations even though it has been shown to affect bond [8–10]. For example, the transfer length for high strength concrete members is less than that predicted by ACI 318-14 and AASHTO [5,6,11].

Transfer length is an important parameter in shear design and in determining allowable stresses. An incorrect estimation of this length can affect the shear capacity of a member and may result in serviceability issues that occur in the end zones at strand release [10,12]. Therefore, there is a need to better estimate transfer length and this can be accomplished by incorporating concrete compressive strength in the transfer length equation.

2. Background

Research on the transfer length in prestressed concrete members began when Hanson and Kaar published their findings on the flexural bond behavior of prestressing strand in 1959 [13]. In 1963, the ACI Building Code implemented equations for these lengths [1]. The ACI formulas were adopted in 1973 by AASHTO [2,14,15]. The equation for transfer length given by ACI 318-14 section R21.2.3 [1,3] is written as follows:

$$L_t = \frac{f_{se}}{20.7} d_b \tag{1}$$

where:

L_t	transfer length (mm)
f_{se}	effective prestress after all losses (MPa)
d_b	strand diameter (mm).

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[*] Corresponding author.
E-mail addresses: axr031@email.uark.edu (A.T. Ramirez-Garcia), rfloyd@ou.edu (R.W. Floyd), micah@uark.edu (W. Micah Hale), jrmarti@cst.upv.es (J.R. Martí-Vargas).

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ACI 318 also states that transfer length can be estimated as 50 strand diameters ($50d_b$) [1,3] and AASHTO uses $60d_b$ (Article 5.11.4.1) [2].

The early transfer length research used stress-relieved Grade 1724 strand with an ultimate strength, f_{pu}, of 1724 MPa, and were typically pretensioned to approximately $0.70f_{pu}$. In current practice, low-relaxation Grade 1862 strand (f_{pu} of 1862 MPa) is used, and is pretensioned up to $0.80f_{pu}$ [2,5,15]. However these changes are not reflected in the code equations.

In 1977, Zia and Mostafa proposed a formula to calculate the transfer length of prestressing strands [7]. Their equation accounted for the effects of strand size, initial prestress, effective prestress, ultimate strength of the prestressing strand, and concrete compressive strength at prestress release (ranging from 14 to 55 MPa). Their research showed that the equations were more conservative (predicted larger values) than the ACI Code when the concrete strength at release is low (14 MPa ≤ f'_{ci} ≤ 28 MPa).

In 1990, Cousins, Johnson, and Zia developed analytical equations for transfer length that included plastic and elastic behavior. In these equations new variables were introduced such as the plastic transfer bond stress coefficient (U'_t), the bond modulus (B), and the prestressing strand area (A_s). Even though Cousins et al. expressed that the ACI 318 Code and AASHTO provisions were inadequate and should be revised, the equations remained unchanged [4].

In 1993, Mitchell et al. studied the influence of concrete strength on transfer length. Their reported concrete strengths at prestress release varied from 21 to 50 MPa and from 31 to 89 MPa at the time of testing. Mitchell et al. developed and proposed an equation for transfer length which predicted shorter values than ACI 318-14 for higher strength concretes [5]. Their findings indicated a reduction in transfer length with increasing concrete compressive strength.

In 1994, Deatherage, Burdette, and Chew cast twenty full scale AASHTO Type I beams with different strand diameters to investigate the transfer length. This work came after the Federal Highway Administration (FHWA) enforced restrictions on the use of Grade 1862 low relaxation seven wire prestressing strand in prestressed concrete girders in October 1988 [16]. Deatherage, Burdette, and Chew considered different strand stresses to formulate an equation for transfer length. The proposed equation resembles the ACI 318-14 and AASHTO equations, but the transfer length is governed by the initial prestress (f_{si}) instead the effective prestress (f_{se}) [1–3]. Although Deatherage, Burdette, and Chew made suggestions on the transfer length equation, no changes were made because the suggestions were more conservative.

In 1996, Russell and Burns investigated the transfer length for 12.7 mm and 15.2 mm diameter strands. They examined several variables such as strand spacing, strand debonding, reinforcement confinement, number of strands per specimen, and size and shape of the cross section [17]. The results showed that the transfer lengths, measured using the "95 Percent Average Maximum Strain" method (95% AMS), for both 12.7 and 15.2 mm strands, were very similar and were larger than ACI 318 and AASHTO standard provisions. Consequently, a new equation for transfer length was proposed by the expression $f_{se}d_b/13.8$; where f_{se} (MPa) and d_b (mm).

In 2006, Marti-Vargas et al. showed that for concretes with compressive strengths in the range of 21 MPa to 55 MPa, the transfer lengths were about 50% to 80% of those calculated by ACI 318-11 [18]. Later, Marti-Vargas et al. investigated the relationship between the average bond stress for the transfer length as a function of the concrete compressive strength [19]. The transfer length decreased as the concrete compressive strength at prestress release increased [8,20,21], and the transfer length depended on the cement content, water content, and bond stress.

In 2008, Ramirez and Russell published a report based on an investigation sponsored by the National Cooperative Highway Research Program (NCHRP-603) [6]. In this project the transfer length was measured in concrete specimens cast with normal-weight and high-strength concrete at compressive strengths up to 103 MPa. The research showed that increasing concrete strength correlated clearly with the shortening of transfer length. As a result, a new equation was recommended for the AASHTO specifications. In particular, this new equation included the concrete compressive strength at release (f'_{ci}). In addition, for concrete compressive strengths at release of 28 MPa, the transfer length was recommended to be $60d_b$, which was the same value provided by AASHTO. On the other hand, for concrete strengths at release greater than 62 MPa, 40 strand diameters ($40d_b$) was the recommended transfer length. Although new equations were proposed to AASHTO, these equations for transfer length were not added to the specifications.

Shown in Table 1 are several equations that were developed for predicting transfer length [4,6,7,14–16,22].

Since 2005, Hale et al. have conducted a significant amount of research on transfer length [11,23–29]. These investigations focused on different types of concrete ranging from normal strength to ultra-high performance concrete. This paper summarizes the findings of the research and those from the literature and proposes an equation that was based on research encompassing many concrete types with different compressive strengths.

3. Research significance

The research project included transfer lengths measured at the University of Arkansas (UA) and from results published in the literature. At the UA, the transfer length was measured for 57 beam specimens. The specimens were cast with a variety of concrete types at a wide range of compressive strengths. In addition, measured transfer lengths data were collected from the literature. This research focuses on the effect of concrete compressive strength (at release and 28-days or time of testing) on transfer lengths. With the data, an equation was developed that encompasses a wide range of concrete types and concrete compressive strengths.

4. Experimental program

4.1. Concrete mixtures

For the specimens cast at the UA, 11 different mixture proportions were developed. These 11 mixtures are shown in Table 2. For the first six mixtures listed in Table 2, the first two letters represent the compressive strength. "NS" refers to normal strength concrete mixtures and "HS" refers to high strength concrete mixtures. The last two letters represent the type of coarse aggregate used in the mixtures. The aggregate type included shale (SH), clay (CL), and limestone (LS). The mixtures containing shale or clay are also lightweight mixtures with a unit weight of approximately 1922 kg/m^3. These first six mixtures were also self-consolidating. The next two mixtures, SCC-I and SCC-III, were normal weight SCC mixtures cast with either Type I or Type III

Table 1

Proposed equations for predicting transfer length (MPa and mm).

Source	Transfer length, Lt
ACI-318/AASHTO LRFD [1]	$L_t = \frac{f_{se}}{20.7} d_b$
Zia and Mostafa, 1977 [7]	$L_t = 1.5 \frac{f_{si}}{f'_{ci}} d_b - 117$
Cousins et al., 1990 [4]	$L_t = \frac{U'_t \sqrt{f'_{ci}}}{2B} + \frac{f_{se} A_s}{\pi d_b U'_t \sqrt{f'_{ci}}}$
Mitchell et al., 1993 [5]	$L_t = \frac{f_{si}}{20.7} d_b \sqrt{\frac{20.7}{f'_{ci}}}$
Deatherage et al., 1994 [16]	$L_t = \frac{f_{si}}{20.7} d_b$
Buckner, 1995 [15]	$L_t = \frac{f_{si}}{20.7} d_b$
Lane, 1998 [14]	$L_t = 4 \frac{f_{si}}{f'_c} d_b - 127$
Kose and Burkett, 2005 [22]	$L_t = 0.045 \frac{f_{si}}{\sqrt{f'_c}} (25.4 - d_b)^2$
Ramirez and Russell, 2008 [6]	$L_t = \frac{315}{\sqrt{f'_{ci}}} d_b \geq 40 d_b$

Table 2
Mixture identifications, number of tests, and compressive strength.

Concrete mixtures	Number of trial beams	Number of L_t tests	f'_{ci} mean, MPa	f'_c mean, MPa
NSSH: Normal strength shale	5	10	28	42
NSCL: Normal strength clay	4	8	31	39
NSLS: Normal strength limestone	4	8	33	52
HSSH: High strength shale	4	8	42	48
HSCL: High strength clay	4	8	43	49
HSLS: High strength limestone	4	8	48	64
SCC-III: Self-consolidating concrete Type III	5	10	51	76
SCC-I: Self-consolidating concrete Type I	8	16	54	84
HSC: High strength concrete	6	12	64	85
UHPC: Ultra high performance concrete	7	14	124	182
LWSCC[a]: Lightweight self-consolidating concrete	6	12	31	46

[a] 12.7 mm diameter strand.

cement. These mixtures were also normal weight (approximately 2323 kg/m^3). Mixture "HSC" was a high strength concrete mixture. Mixture "UHPC" was a commercially available ultra-high performance concrete mixture. The final mixture "LWSCC" was a lightweight SCC mixture proportion that was developed by prestressed concrete beam fabricator. The mixture proportions were discussed in greater details in earlier publications by the authors [11,23–30].

The number of beams cast from each mixture and the number of transfer length tests performed on beams cast with that particular mixture are also presented in Table 2. Fifty-one beams were cast with 15.2 mm diameter [24,26,29] strands, and six beams were cast with 12.7 mm diameter strands [27].

Also shown in Table 2 is the mean compressive strength at release and at 28 days for each mixture. The compressive strengths at release using 15.2 mm strand ranged from 23 MPa to 155 MPa, and the 28 day strengths ranged from 34.5 MPa to 199 MPa. Furthermore, for 12.7 mm diameter strand the compressive strengths at release ranged from 24 MPa to 37 MPa, and the 28 day strengths ranged from 41 MPa to 52 MPa.

4.2. Beam fabrication

At the UA, 57 fully bonded, prestressed, precast beams have been cast since 2005. Each beam had a rectangular cross-section of 165 mm by 305 mm and was 5.5 m length. The beams contained two, low relaxation wire Gr. 1862 prestressing strands located a distance of 254 mm, measured from the top (compression fiber) of the beam to the centroid of the strand as shown in Fig. 1. Strand diameters of 12.7 mm and 15.2 mm were included in the study. Two No. 19, Gr. 414 reinforcing bars were located near to 51 mm from the top of each beam. The beams were reinforced with No 6 smooth bars spaced at 150 mm. The beams were cast with mixtures shown in Table 2 [24,26,27,29]. Two beams were cast simultaneously on a 15.2 m prestressing bed. The strands were tensioned to 75% f_{pu}, 1397 MPa.

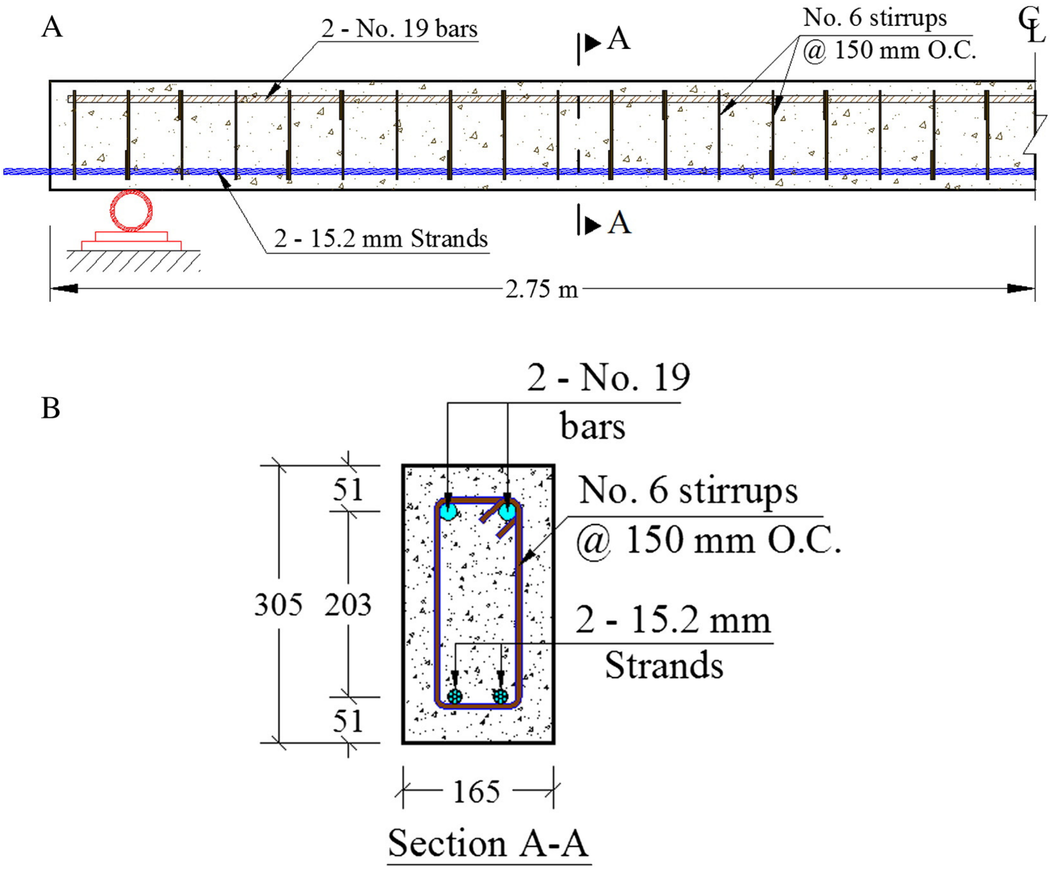

Fig. 1. Beam section and reinforcement detail.

4.3. Bond quality assessment

The Standard Test for Strand Bond (STSB) was used to assess the quality of the strands used in the UA study. The force required to induce 2.54 mm of free end slip for each specimen exceeded the 4899 kg minimum required for individual specimens. For the three sources of strands used in the study, the average pull out values of 8700, 10,083, and 9339 kg exceeded the minimum requirement of 5715 kg. Thus, the results showed that the strands were of good quality.

4.4. Instrumentation

Before prestress release, detachable mechanical (DEMEC) strain gauge targets were attached to the beam at the level of the prestressing strand (Fig. 2). These targets were placed at both ends of the beam on both faces [7,17,31–34]. The first target was approximately placed at 25.4 mm from the beam end, and the other DEMEC points were placed at 100 mm intervals. The prestress was gradually released approximately 24 h after casting. This was accomplished by releasing the pressure in the hydraulic strand tensioning system. Each beam specimen was labeled based on the concrete type along with a beam number. For instance, the first beam cast using SCC with Type I cement was labeled SCCI-1 [11,23,25,28]. Surface strains were assessed using a digital DEMEC strain gauge with 200 mm gauge length. Strain readings were taken immediately before and after prestress release and at 3, 5, 7, 14, and 28 days (Fig. 3). Transfer lengths were determined using the 95% Average Maximum Strain method (AMS) [17]. Transfer length was measured for both beam ends which results in 114 total tests as is shown in Table 2.

Fig. 3. DEMEC measurements.

5. Transfer length analysis

5.1. Measured transfer length data

The measured minimum, average, and maximum transfer lengths at release and at 28-days are presented in Table 3. Additionally, the average concrete compressive strengths at release (f'_{ci}) and at 28-days (f'_c), the average of the effective strand stress after all losses (f_{se}), and the predicted transfer lengths using ACI 318-14 & AASHTO are presented.

As shown in Table 3, the maximum measured transfer length for all beams was 1090 mm. This occurred in the NSSH series which also had the lowest concrete compressive strength at release. This value was greater than the predicted value of 792 mm by approximately 37.5%. The average transfer length for all NSSH beam was 733 mm at release which was 92.4% of the predicted value. At the other extreme, the predicted transfer length for the UHPC series was over 250% greater than the average measured transfer length. The UHPC series possessed the highest compressive strength at release and at 28 days of age. Table 3 shows that once the compressive strength at release achieved 42 MPa or greater, all measured transfer lengths were less than the values predicted by ACI 318-14 and AASHTO.

The data was analyzed using a power regression which is shown in Fig. 4. The measured transfer lengths are plotted versus the concrete compressive strength. The measured transfer length at both beam ends is plotted (L = live end and D = dead end) along with the compressive strength at release and at 28-days. The data in Fig. 4 confirms that the measured transfer lengths decreased as the concrete strengths increased [6,35]. Based on the data shown in Fig. 4, concrete compressive strength should be included in the transfer length equations [8,20,22,35].

Several researchers have examined the influence of other variables on transfer length [4,7,8,19,20,22,31,36]. Based on this previous research, two variable sets were included in this study. For the first set, concrete compressive strength at release (f'_{ci}), initial prestress (f_{si}) (75% $f_{pu} = 1397$ MPa), and strand diameter (d_b) were examined. The variables for the second set were concrete compressive strength at release (f'_{ci}), effective strand stress after all losses (f_{se}), and strand diameter (d_b). Statistical analysis was conducted for the two variable sets, and from this analysis the first set of variables (f'_{ci}, f_{si}, and d_b) were chosen because these variables had a greater affect transfer length

Fig. 2. Placement of DEMEC points.

Table 3
Measured transfer lengths and predicted lengths.

Series	f'_{ci}, MPa	f'_c, MPa	f_{se}, MPa	Reported transfer lengths (mm): release			Reported transfer lengths (mm): 28 days			ACI/AASHTO
				Min.	Avg.	Max.	Min.	Avg.	Max.	Predicted
NSSH	28	42	1076	505	733	1090	559	681	970	792
NSCL	31	39	1069	495	597	815	424	635	841	787
NSLS	33	52	1166	450	557	991	470	609	1031	858
HSSH	42	48	1146	409	520	681	361	426	521	843
HSCL	43	49	1154	361	486	780	399	487	610	850
HSLS	48	64	1215	460	503	551	490	531	640	895
SCC-III	51	76	1216	381	457	584	368	483	610	895
SCC-I	54	84	1244	394	507	635	343	512	673	916
HSC	64	85	1256	394	506	635	432	579	724	925
UHPC	124	182	1297	267	358	432	279	361	457	955
LWSCC[a]	31	46	1186	381	525	838	330	510	686	873

[a] Strand 12.7 mm diameter was used in this case.

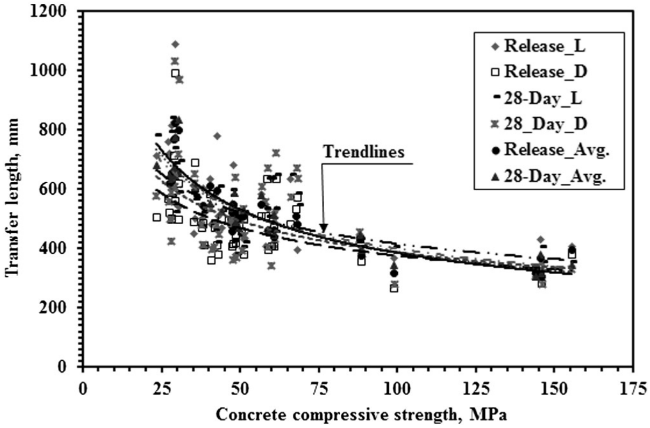

Fig. 4. Transfer length analysis—power regression.

at release [5,7]. Consequently, an equation for transfer length (Eq. 2) was derived and is shown below:

$$L_t = 25.7\left(\frac{f_{si}}{f'_{ci}} d_b\right)^{0.55} \tag{2}$$

where:

f_{si} initial prestress (MPa)
f'_{ci} concrete strength at prestress release (MPa)
d_b nominal strand diameter (mm).

Fig. 5 shows the ratio between predicted and measured transfer length for the ACI/AASHTO, NCHRP-603, and the proposed equation (Eq. 2). The ratio due to the proposed equation and NCHRP-603 are similar when the concrete strength at release is less than 62 MPa. The ratio is almost equal to one when the concrete strength at release is equal to 62 MPa. At compressive strengths greater than 62 MPa, the proposed equation provides a better estimate than the NCHRP-603 equation. At compressive strengths less than 41 MPa, the ACI 318-14 and AASHTO equations are more accurate than the proposed and NCHRP-603 equations. In addition, the ratio of the ACI 318-14 and AASHTO equations increases suddenly for higher compressive strength ($f'_{ci} \geq 62$ MPa) while the ratio due to the proposed equation remains closer to one.

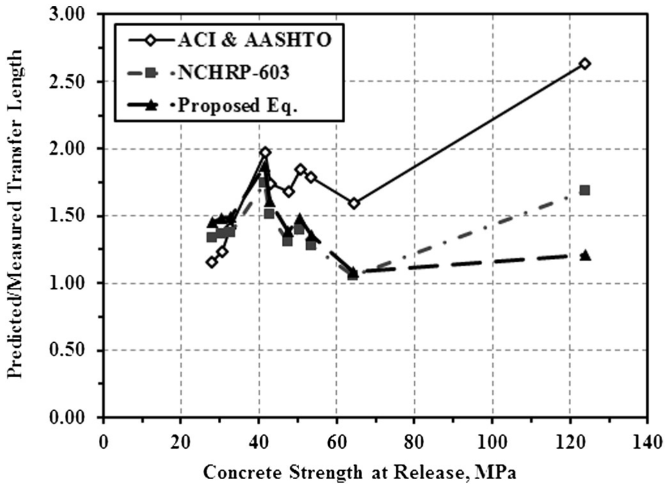

Fig. 5. Ratio of predicted to measured transfer length.

5.2. Transfer length data from the literature

Transfer length data [4–6,16,17,19,33,34,37–41] were collected from the literature in order to examine the accuracy of the proposed equation. For 12.7 mm strands, 293 transfer length tests were identified in the literature, and this number was reduced to 180 data points (Table 4). Many researchers reported transfer lengths for the dead ends, live ends, or the average of both ends. Therefore, the 180 data points represent the total number of transfer length analyzed, and each transfer length was the average transfer length of both ends of a beam. For 15.2 mm strands, 345 transfer length measurements were identified in the literature and then reduced to 139 data points (Table 5). This number represents the average transfer length for 139 beam ends.

The measured transfer lengths from the data set were plotted against the concrete compressive strength at release (f'_{ci}) which ranged from 19 MPa to 155 MPa as shown in Figs. 6 and 7. For most of the data collected from the literature, the concrete compressive strengths at release ranged from 19 MPa and 69 MPa. However, there is a limited amount of data that includes concrete compressive strengths at release over 69 MPa [25]. Both figures show the decrease in transfer length as concrete compressive strength at release increases. The figures also show the range of transfer lengths at lower concrete compressive strengths. For 12.7 mm strands, the transfer lengths ranged from approximately 250 mm to 1900 mm at 28 MPa. The highest transfer lengths were reported by Cousins et al. (1990). These values may have been caused by unreported factors such as poor strand surface condition [4]. The data also show the lack of change in transfer length at high release strengths.

5.3. Data reduction

To determine the accuracy of the proposed equation, outliers in the data set were removed. Outliers were determined based on the average transfer length ratio and standard deviation. The transfer length ratio was calculated by dividing the predicted transfer length by the measured transfer length. Predicted transfer lengths were calculated using the ACI 318-14 equation and Eq. 2. Some assumptions were made in order to use these equations. These assumptions included a low relaxation wire, Grade 1862 strand (12.7 mm and 15.2 mm diameter) with an ultimate strength, f_{pu}, of 1862 MPa, an initial prestress of 1397 MPa ($f_{si} = 0.75 f_{pu}$), and an effective prestress after all losses of 1117 MPa ($f_{se} = 0.60 f_{pu}$) [20]. Using these values, the predicted transfer lengths obtained using ACI 318-14 were 686 mm and 823 mm for 12.7 mm and 15.2 mm strand, respectively.

Figs. 8 and 9 show the transfer length ratios (predicted/measured) versus the measured transfer lengths. The transfer length ratios were calculated using the data set and the values using the ACI 318-14 equation. These figures also show the average transfer length value (AV), the standard deviation (SD), the underestimated values (UV), and the overestimated values (OV), and the upper bound (AV + SD) and lower bound (AV − SD). For the 12.7 mm strand, the average transfer length ratio was 1.32 with a standard deviation of ±0.35. Furthermore, since the predicted transfer length using the ACI 318-14 equation was constant for both strand sizes (686 mm and 823 mm), the plotted ratios follow the same power trend line as shown in Figs. 8 and 9. Figs. 10 and 11 show the values predicted using Eq. 2. Since the predicted transfer length values using Eq. 2 are dependent on the concrete strength at release (f'_{ci}), the predicted transfer length is not constant unlike the values determined using ACI 318-14. This is reflected in the plot of the data in Figs. 10 and 11.

The following conclusions can be determined from Figs. 8 and 10 (12.7 mm diameter strand). The average transfer length ratio using ACI 318-14 was 1.32, and its SD was ±0.35 while the average transfer length ratio using Eq. 2 was 1.46 and its SD was ±0.38. Therefore, the ACI 318-14 equation overestimates transfer length by 32% while the

Table 4
Transfer lengths from the literature for 12.7 mm strand.

Literature source	Number of tests	Data analyzed	Reported transfer length, mm			Average f'_{ci}, MPa
			Min.	Avg.	Max.	
Cousins et al., 1990	20	20	813	1262	1880	35
Mitchell et al., 1993	14	8	367	513	711	40
Deatherage et al., 1994	16	16	457	602	914	33
Russell and Burns, 1996	34	17	432	748	978	30
Rose and Russell, 1997	30	15	300	392	587	29
Russell and Burns, 1997	12	6	661	1050	1461	25
Mahmoud et al., 1999	8	8	350	469	600	41
Oh and Kim, 2000	36	18	463	606	826	40
Hodges, 2006	6	3	343	474	699	36
NCHRP-603, 2008 (A/B)	30	15	311	412	554	52
NCHRP-603, 2008 (D)	31	16	391	597	937	53
Bhoem et al., 2010	12	6	343	411	465	47
Marti-Vargas et al., 2012	12	12	400	533	650	39
Myers et al., 2012	8	8	351	460	630	39
UA (release)	12	6	406	525	686	31
UA (28-day)	12	6	394	510	610	46
Total number of tests	293	180				

Note: Ramirez and Russell, 2008 (NCHRP R-603).

Table 5
Transfer lengths from the literature for 15.2 mm strand.

Literature source	Number of tests	Data analyzed	Reported transfer length, mm			Average $f'ci$, MPa
			Min.	Avg.	Max.	
Cousins et al., 1990	10	10	1118	1435	1727	33
Mitchell et al., 1993[a]	12	6	305	545	803	40
Deatherage et al., 1994	8	8	889	1032	1270	33
Russell and Burns, 1996	40	20	711	1016	1264	31
Russell and Burns, 1997	13	8	762	1043	1245	28
Oh and Kim, 2000	36	18	539	758	1022	40
NCHRP-603, 2008 (A6)	22	11	475	667	785	51
UA (release)	102	30	305	524	824	64
UA (28-day)	102	28	305	532	833	89
Total number of tests	345	139				

UA: University of Arkansas.
[a] Strand 15.75 mm.

proposed equation, Eq. 2, overestimates by 46%. Although Eq. 2 had a greater standard deviation than ACI 318-14 (0.38 vs 0.35), the total number of measured transfer lengths between UV and OV lines represents 39% of the data set analyzed. This represents 10% more than the ACI 318-14 equation. The percentage of excluded data for the ACI 318-14 equation is 71% which represents 10% more than the proposed equation, Eq. 2. Therefore, more data are represented between the lower and upper bounds for Eq. 2 which means Eq. 2 better represents the measured transfer length values obtained from the literature than the ACI 318-14 equation.

The same analysis was performed using the data set of 15.2 mm diameter strand. The average transfer length ratio using ACI 318-14 was 1.17 with a SD of ±0.44. The average transfer length ratio was 1.12 using Eq. 2 and had a SD of ±0.31. For the 15.2 mm strands, Eq. 2 overestimated transfer length by 12% compared to 17% for ACI 318-14. The total measured transfer lengths between the lower and upper bounds for Eq. 2 represent 72% of the data which is 9% more than that represented by ACI 318-14.

5.4. Influence of compressive strength on transfer length

To determine the accuracy of Eq. 2, its predicted values were compared to those from other proposed equations. The other proposed equations include those listed in Table 1 with the exception of the Buckner equation. This equation was not included in the study because of its similarity to the Deatherage equation which was included. In order to use some of the equations shown in Table 1, additional inputs were necessary. Values for f_{pu}, f_{si}, and f_{se} were assumed in the previous task, but additional values were needed for the Cousins et al. equation. Those values included the plastic transfer bond stress coefficient ($U'_t = 0.556$), the bond modulus ($B = 0.0815$ MPa/mm), and the area of the prestressing strand ($A_s = 140$ mm^2) for 15.2 mm diameter strand.

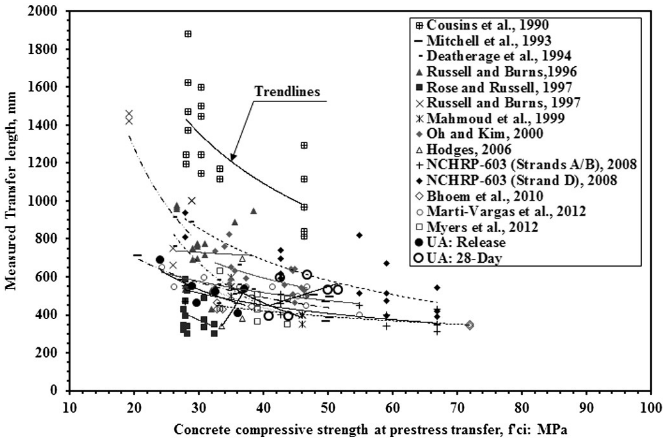

Fig. 6. Transfer length of 12.7 mm strand from the literature.

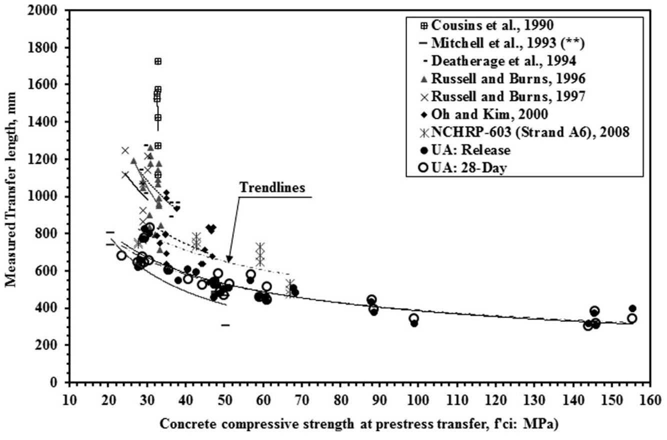

Fig. 7. Transfer length of 15.2 mm strand from the literature ($^{**} = 15.75$ mm).

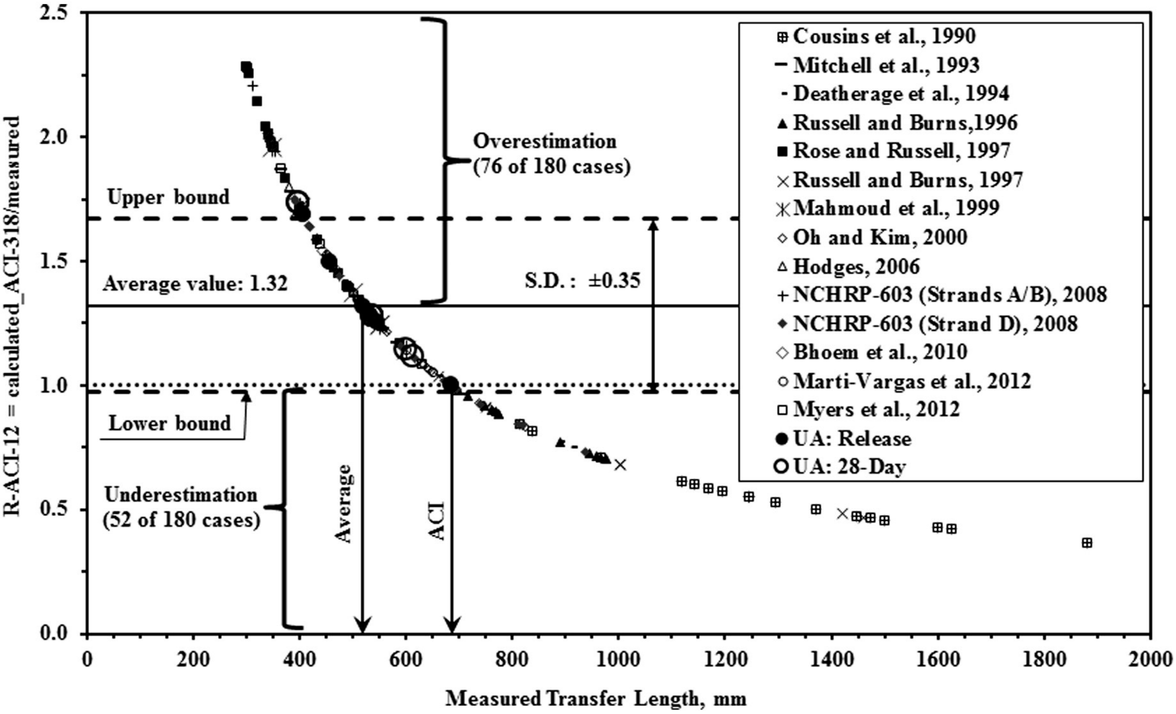

Fig. 8. Transfer length ratio using ACI 318-14 for 12.7 mm strand.

Using these values, the transfer lengths were calculated, normalized with respect to the nominal strand diameter, and plotted as shown in Fig. 12.

For this analysis, the concrete compressive strength at release was varied from 28 MPa to 83 MPa while the 28 day concrete strength ranged from 41 MPa to 110 MPa. As shown in the Fig. 12, the ACI 318-14, AASHTO, and Deatherage et al. equations are not dependent on concrete strength and therefore their predicted transfer length values are constant for all strengths.

When the concrete strength at release and at 28-days were 28 MPa and 41 MPa respectively, all predicted transfer length values using the equations in Table 1 were greater than the predicted value using ACI 318-14. On the contrary, when concrete strength at release is 62 MPa or more, all equations except for the Deatherage et al. equation predict

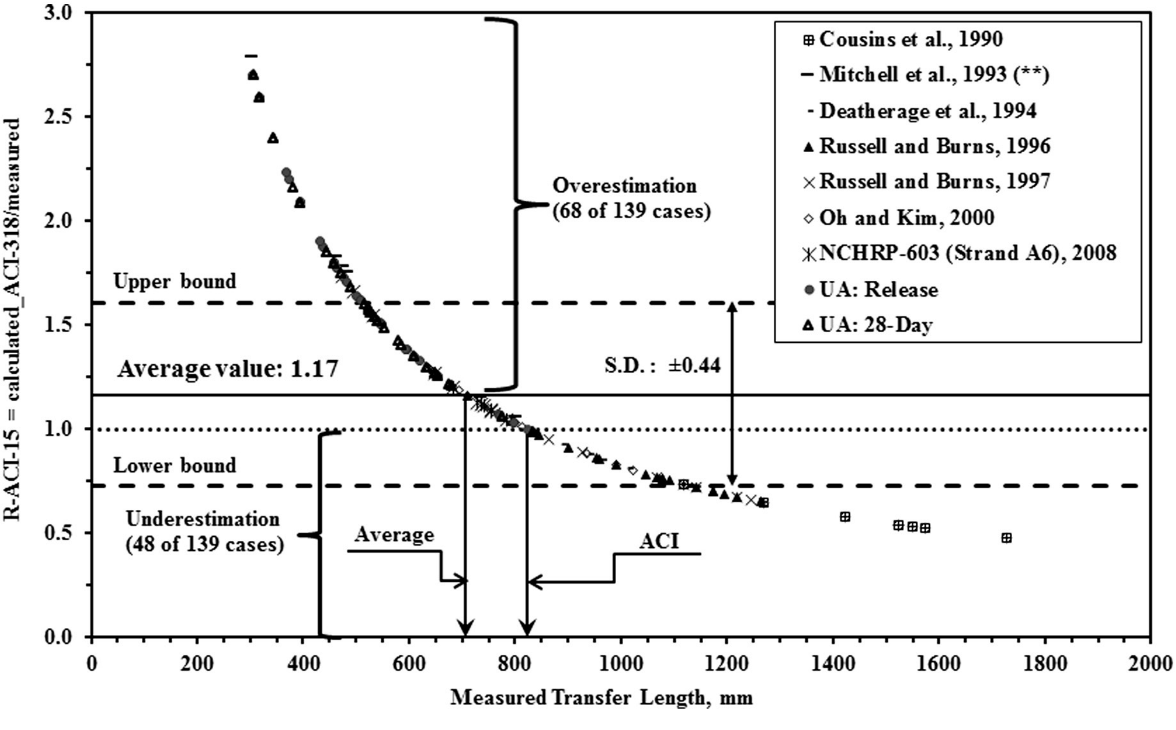

Fig. 9. Transfer length ratio using ACI 318-14 for 15.2 mm strand.

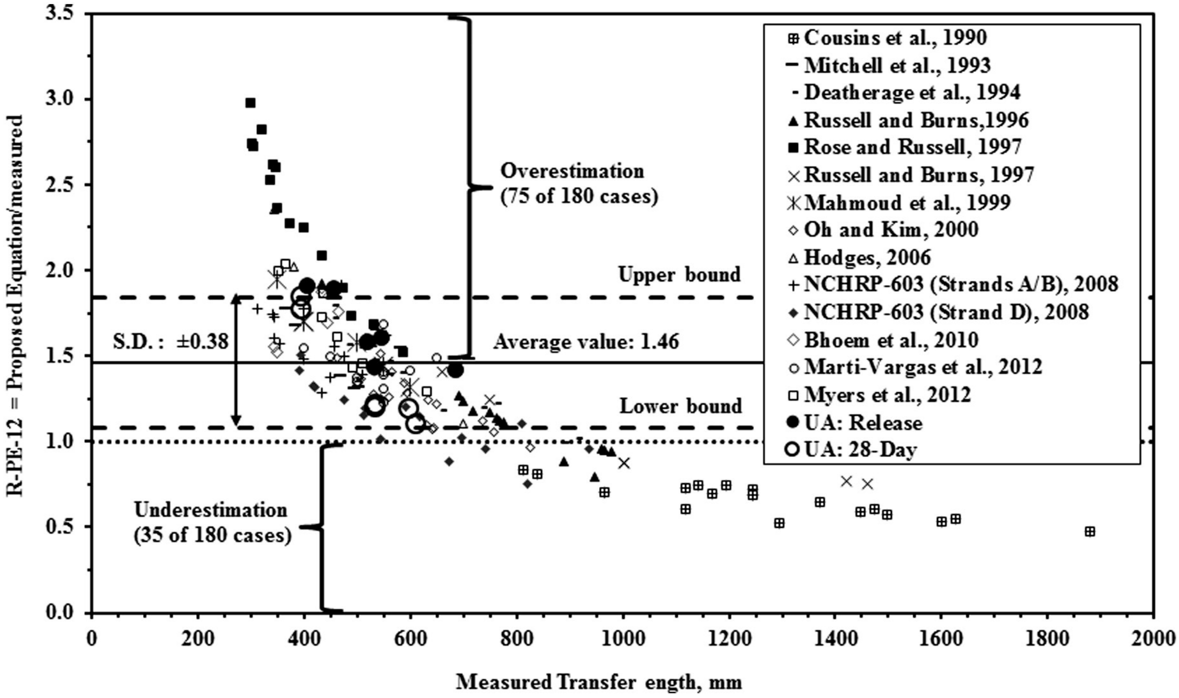

Fig. 10. Transfer length ratio using Eq. 2 for 12.7 mm strand.

a transfer length that is less than that predicted by ACI 318-14. The UA equation, Eq. 2, predicts values that follow similar trends as the other equations (excluding ACI 318-14, AASHTO, and Deatherage et al.). Eq. 2 predicts values which are slightly different than those of the NCHRP-603 equation. For instance, Eq. 2 predicts larger transfer length values at lower compressive strengths and shorter values at higher compressive strengths.

It should be noted that Zia and Mostafa's equation for transfer length [7] was not recommended for compressive strengths over 55 MPa. For release strengths of 62 MPa and 83 MPa, their equation predicts transfer lengths that are approximately 40 to 50% less than the minimum limit recommended by NCHRP-603 ($40d_b$). In addition, Fig. 12 shows two important conclusions which are:

1. When the concrete strength at release and 28-days increases, the normalized transfer length decreases for all estimated values except those predicted using the ACI 318-14 (R21.2.3) and Deatherage et al. equations. Value predicted using these two equations are constant

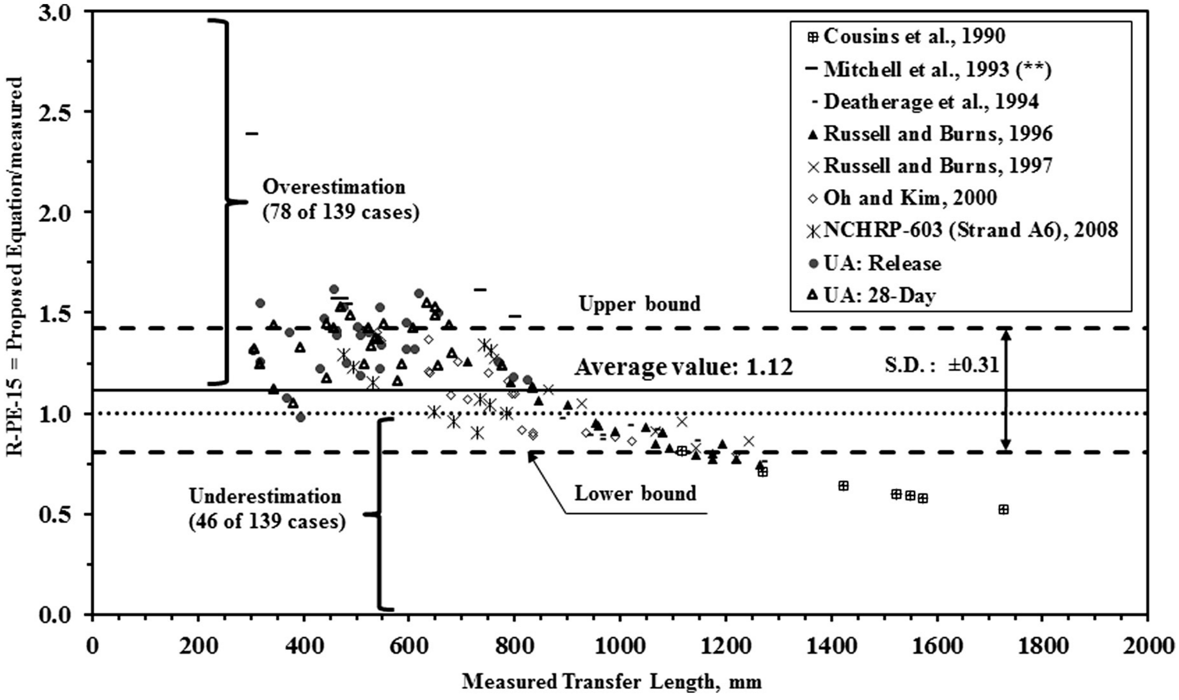

Fig. 11. Transfer length ratio using Eq. 2 for 15.2 mm strand.

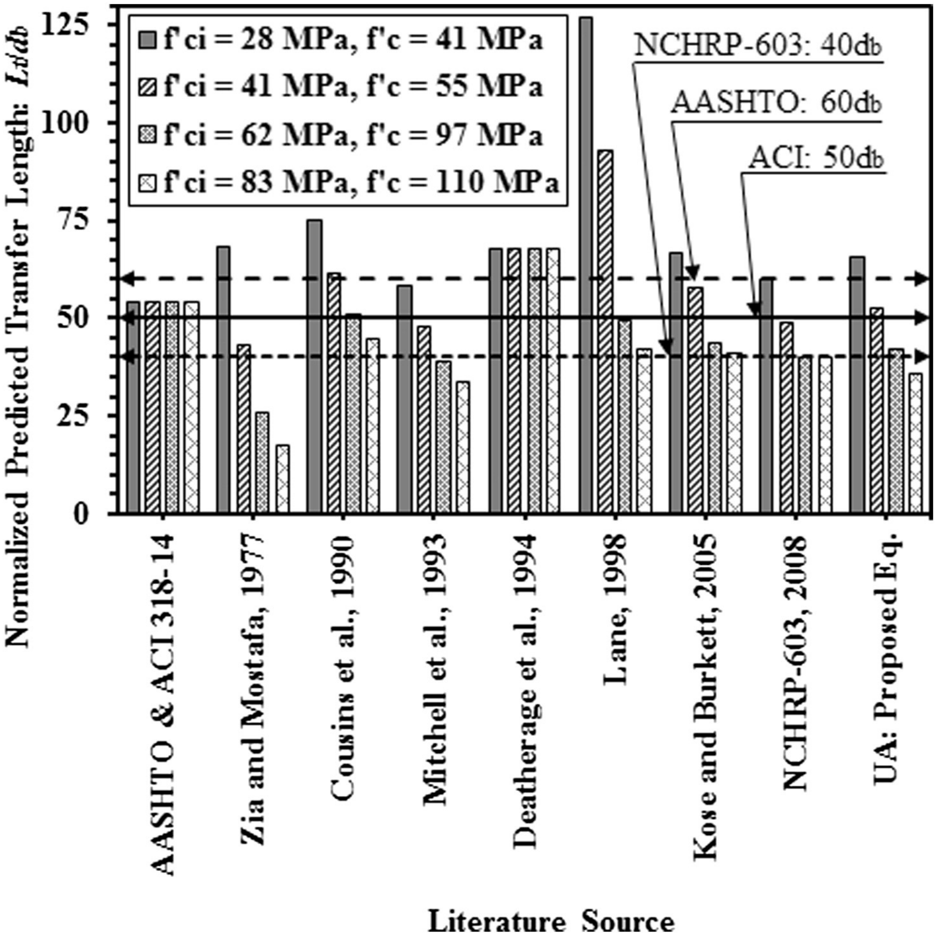

Fig. 12. Comparison of normalized transfer lengths.

due to the fact that the transfer length does not depend on concrete compressive strength.

2. For compressive strength at release of 83 MPa, the transfer lengths for 5 of the 7 proposed equations which are function of concrete compressive strength predict values that are lower or equal values than the minimum transfer length ($40d_b$) [6]. The exceptions are the Kose and Burkett's equation and Lane's equation. However, at a concrete strength (f'_c) greater than 117 MPa, both equations predict transfer lengths less than $40d_b$.

6. Summary and conclusions

The research project examined the measured transfer lengths of 57 prestressed concrete beams cast with a variety of different concrete types. The concrete types included normal strength (NS), high strength (HS), self-consolidating concrete (SCC), ultra-high performance (UHP), and light weight (LW) concrete. Fifty one beams were fabricated with 15.2 mm, Grade 270, seven wire low relaxation prestressing strand. The concrete compressive strengths at release for those 51 beams ranged from 23 MPa to 155 MPa. Six beams were fabricated using 12.7 mm diameter strands with concrete compressive strengths at release between 24 MPa and 31 MPa. Measured transfer lengths were determined using concrete surface strains along with the AMS method. The UA data was analyzed using the power regression in order to develop a new transfer length equation. A power regression was chosen to develop this new equation because this repression provided a better fit than the linear regression. This was due to the influence of concrete compressive strength on the transfer length. In addition, measured transfer lengths from the literature were collected and analyzed and compared with ACI 318-14, ACI ($50d_b$), AASHTO ($60d_b$), NCHRP-603 ($40d_b$), equations from the literature, and the proposed equation, Eq. 2. Based on the investigation, the followings conclusions were made:

1. Transfer length in prestressed concrete members decreases as concrete compressive strength increases. Research results also show that the ACI 318-14 and AASHTO equations overestimate transfer lengths in members containing concrete with high compressive strengths. Therefore, concrete compressive strength should be a factor in predicting transfer length.
2. Based on the results of the study, Eq. 2 and the ACI 318-14 equation are recommended when the concrete compressive strength at release is less than 34.5 MPa. Based on the UA experimental data, $40d_b$ should be used as minimum transfer length for members containing concrete with compressive strengths at release greater than 34.5 MPa but less than 55 MPa. When the concrete compressive strength at release is greater than 55 MPa, transfer length can be taken as $33d_b$. There is little change in transfer length as concrete compressive strength at release increases beyond 55 MPa.
3. The proposed UA equation, Eq. 2, is based on experimental data with good strand bond (STSB values of 117 MPa or more). For strands with poor surface quality, further investigation is needed in order to determine the applicability of the UA equation.
4. Measured transfer length values collected from the literature were compared to values predicted using the ACI 318-14, AASHTO, and NCHRP-603 equations. The predicted values were greater than the mean experimental values for approximately 18% of the beams containing 12.7 mm diameter strand and 40% for beams containing15.2 mm diameter strand.

5. The total data between the lower and upper bounds, [AV ± SD], was 53% for the measured transfer length ratios using ACI 318-14 and 64% for the same ratio using Eq. 2 for 12.7 mm diameter strand. For 15.2 mm strands, the total data within this range was 63% when ACI 318-14 was used and 72% when Eq. 2 was used. Therefore, the proposed question, Eq. 2 better represents the experimental data than the ACI 318-14 equation.
6. Current equations do not adequately estimate transfer length for higher strength concretes. Since the 1970s, many researchers have recommended including concrete strength in the equation for transfer length. The proposed equation, Eq. 2, does include concrete strength and more accurately estimates transfer length for beams containing high strength concrete.

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