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Influence of concrete strength on development length of prestressed concrete members

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ABSTRACT

Fifty seven prestressed concrete beams were fabricated at the University of Arkansas (UA) to determine the influence of concrete strength on the development length of seven wire prestressing strand. The variables considered in the investigation were the concrete compressive strength (f'_c), which ranged from 34.5 MPa to 199 MPa, and the strand diameter, which included 12.7 mm and 15.2 mm. The beams were cast with concrete types which included self-consolidating concrete, high strength concrete, lightweight concrete, and ultra-high performance concrete. Development length was determined through flexural testing. The research project also summarized the findings of several studies from the literature. The measured development lengths were compared to those calculated using the American Concrete Institute (ACI 318-14) prediction equation for development length. The results showed that compressive strength affects the development length and the ACI 318 equation overestimates development length. Also, a development length equation was developed and presented in the paper.

1. Introduction and background

When designing prestressed concrete members, engineers must determine the development length of the prestressing strands. The development length is the sum of the transfer length and the flexural bond length. The transfer length is the distance from the free end of the prestressing strand necessary to fully bond the strand to the concrete. The flexural bond length, L_b, is the length required, beginning at the end of the transfer length, to fully develop the strength of the strand. Therefore the development length, L_d, is the distance from the free end of the strand to the section where the nominal moment can be resisted [1]. The transfer length, flexural bond length, and development length are shown in Fig. 1. The ACI 318-14 (Eq. (1.a)) and AASHTO (Eq. (1.b)) equations for estimating development length are shown below.

$$L_d = \frac{f_{se}}{20.7}d_b + \frac{1}{6.9}(f_{ps} - f_{se})d_b \tag{1.a}$$

$$L_d = \frac{\kappa}{6.9}\left(f_{ps} - \frac{2}{3}f_{se}\right)d_b \tag{1.b}$$

The AASHTO equation is similar to the ACI 318-14 equation for development length, except the development length has been modified by a k factor (Eq. (1.b)) as recommended by the 1988 Federal Highway Administration (FHWA) memorandum [2–4]. The k factor amplifies the development length calculated by the ACI 318-14 equation. For pretensioned members (panels, piles, etc.) with a depth less than 0.60 m, $k=1.0$ and for other pretensioned members with a depth less than 0.60 m, $k=1.6$. For debonded strands, k=2.0.

The ACI 318-14 equation was implemented in 1963 based on investigations conducted in the 1950s [1,5], and later the ACI 318-14 equation was adopted by AASHTO LRFD Bridge Design Specifications (hereafter referred to as AASHTO) in 1973 [2,3,6]. Concrete technology has advanced since the equations were adopted, but the equations have remained unchanged. For example, the compressive strength of the concrete used in the seminal strand bond research by Hanson and Kaar ranged from 26 to 54 MPa for the development length tests [5]. The use of high strength concrete has become common in prestressed concrete bridge girders. Higher concrete compressive strengths can increase span length, decrease girder height, and eliminate the total number of girders in a bridge when compared to bridge girders cast with normal strength concrete [7]. Since the original equations were based on lower strength concrete and the compressive strength being used

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Notation

A_s	area of the prestressing strand (mm^2)
d_b	diameter of the strand (mm)
f'_{ci}	concrete compressive strength at prestress release (MPa)
f'_c	concrete compressive strength at 28-days or time of testing (MPa)
f_{si}	initial prestress (MPa)
f_{se}	effective prestress (MPa)
f_{ps}	stress at nominal strength of the member (MPa)
L_{fb}	flexural bond length
L_e	embedment length (mm)
L_d	development length (mm)
k_e	normalized embedment length factor
k_p	normalized predicted development length factor
U'_t	plastic transfer bond stress coefficient
U'_d	plastic development bond stress coefficient
B	bound modulus (MPa/mm)

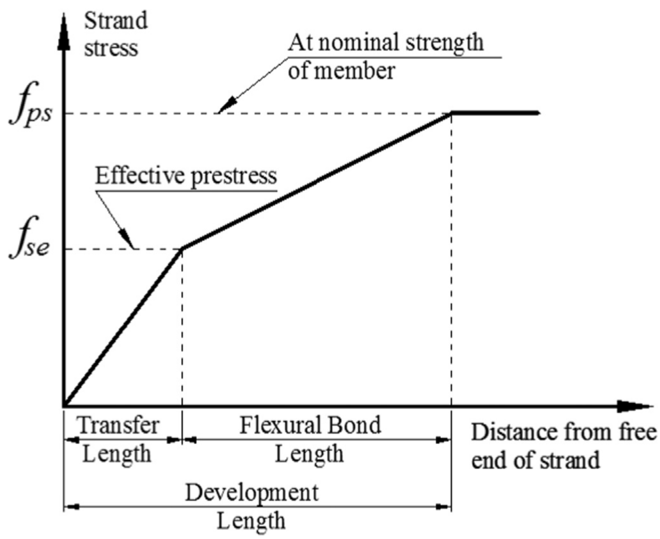

Fig. 1. Strand stress vs. length, ACI 318-11 (R12.9) and AASHTO LRFD (C5.11.4.2-1).

in current prestressed concrete applications is increasing, it is necessary to determine the applicability of the development equations given by the ACI318-14 and AASHTO.

Since the inception of prestressed concrete research, researchers have investigated the bond between the concrete and prestressing steel. The current equations provided by ACI 318-14 and AASHTO are a function of the effective prestress (f_{se}), stress at nominal strength of the member (f_{ps}), and the diameter of the strand (d_b) [1,6]. Updated equations have been published to amend the current equations, but most have not been implemented by ACI 318-14 or AASHTO. Current investigations have shown that the initial prestress (f_{si}) and concrete compressive strength, both at prestress release (f'_{ci}) and at 28-days (f'_c), affect both transfer and development lengths [8–12]. Researchers have also shown the measured transfer and development lengths for high strength concrete members are less than those values predicted using ACI 318-14 and AASHTO equations [9,10,13]. As such, the question has risen as to whether concrete compressive strength should be included as a principal variable in development length equations.

Several variables have been investigated in order to improve the accuracy of the development length equation. These variables include the concrete compressive strength at prestress release (f'_{ci}) and at the time of testing (f'_c), the initial prestress in the strand (f_{si}), the effective prestress in the strand after all losses (f_{se}), the stress in the strand at nominal strength (f_{ps}), and the nominal strand diameter (d_b). Although these variables are essential for development length, other variables can be considered, such as friction between the strand and concrete, type of strand release, strand surface condition, confining reinforcement around the strand, and type of loading [5,8,10,11,14,15]. Table 1 contains several equations for transfer lengths and flexural bond lengths.

Table 1
Proposed equations for predicting development length (Ld=Lt+Lfb) from the literature (in MPa and mm).

Source	Transfer length, L_t	Flexural bond length, L_{fb}
ACI-318/ AASHTO LRFD [1]	$L_t = \frac{f_{se}}{20.7} d_b$	$L_{fb} = 0.145(f_{ps} - f_{se}) d_b$
Zia and Mostafa [11]	$L_t = 1.5 \frac{f_{si}}{f'_{ci}} d_b - 117$	$L_{fb} = 0.181(f_{pu} - f_{se}) d_b$
Cousins et al. [8]	$L_t = \frac{U'_t \sqrt{f'_{ci}}}{2B} + \frac{f_{se} A_s}{\pi d_b U'_t \sqrt{f'_{ci}}}$	$L_{fb} = (f_{ps} - f_{se}) \left(\frac{A_s}{\pi d_b U'_d \sqrt{f'_c}} \right)$
Mitchell et al. [9]	$L_t = \frac{f_{si}}{20.7} d_b \sqrt{\frac{20.7}{f'_{ci}}}$	$L_{fb} = 0.145(f_{ps} - f_{se}) d_b \sqrt{\frac{31}{f'_c}}$
Deatherage et al. [4]	$L_t = \frac{f_{si}}{20.7} d_b$	$L_{fb} = 0.218(f_{ps} - f_{se}) d_b$
Buckner [3]	$L_t = \frac{f_{si}}{20.7} d_b$	$L_{fb} = 0.145\lambda(f_{ps} - f_{se}) d_b$ $1 \leq \lambda \leq 2$
Lane [2]	$L_t = 4 \frac{f_{si}}{f'_c} d_b - 127$	$L_{fb} = \frac{6.4(f_{pu} - f_{se})}{f'_c} d_b + 381$
Kose and Burkett [25]	$L_t = 0.045 \frac{f_{si}}{\sqrt{f'_c}} (25.4 - d_b)^2$	$L_{fb} = 203.2 + 0.19 \frac{(f_{pu} - f_{si})}{\sqrt{f'_c}} (25.4 - d_b)^2$
Ramirez and Russell [10]	$L_t = \frac{315}{\sqrt{f'_{ci}}} d_b \geq 40 d_b$	$L_{fb} = \frac{591}{\sqrt{f'_c}} d_b \geq 100 d_b$

Some of the proposed equations in Table 1 were developed for concrete with compressive strength at prestress release between 14 MPa and 55 MPa [11]. Other investigators have studied the transfer and development lengths of prestressed concrete containing high-strength and normal-weight concrete which included compressive strengths up to 103 MPa [10] and 199 MPa [13,16,17]. These investigations focused on a wide range of concrete including conventional concrete and ultra-high performance concrete. The research showed that increasing concrete strength correlated clearly with shortening of the transfer and development lengths.

Some flexural bond length equations [3,4,11] use the same equation given by ACI-318-14 [1], but includes a modification factor, λ, which varies from 0.145 to 0.290 (1–2 for f_{pu} and f_{se} in *ksi*, and d_b in inches) [3]. For example, some researchers [11]