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Effect of concrete compressive strength on transfer length

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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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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 $\le f'_{ci} \le$ 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]	$L_t = \frac{315}{\sqrt{f'_{ci}}} d_b \ge 40 d_b$