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Analytical prediction of transfer length in prestressed self-consolidating concrete girders using pull-out test results

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ABSTRACT

While self-consolidating concrete (SCC) is comparable to conventional concrete (CC) in terms of strength, the comparability of SCC's bond to steel is less well-defined. A keen understanding of SCC's bond strength is essential to advance SCC within the prestressed concrete industry. This study presents an analytical method for predicting the transfer length of steel strands in prestressed girders using pull-out test results. The experimental data from a series of 56 pull-out tests is utilized to derive bond stress–slip relationships for 12.7 mm steel strands embedded in SCC and CC. Modification factors are used to correlate pullout bond stresses to transfer bond stresses in prestressed members, and the modified relationships are integrated in three-dimensional finite element models to predict transfer lengths in prestressed SCC girders. The analytical predictions correlate well with experimental results and transfer length requirements of current US design codes.

1. Introduction

In the early 1980's, the number of skilled workers in Japan's construction industry had fallen to a level which spurred concerns over the quality of the country's concrete infrastructure [1]. To improve concrete durability without the need for skilled labor, researchers developed a high performance concrete which would compact into formwork via its own weight. Today, self-consolidating concrete (SCC) has emerged as a viable alternative to conventional concrete (CC) in many structural applications, particularly those which require dense reinforcement or complex geometry. Its unique workability and propensity to reduce construction time and cost have made SCC an intriguing material to the international design community.

Inconclusive research on SCC behavior in prestressed members has thus far limited the technology's impact on the United States' prestressed concrete industry. A keen understanding of SCC's bond strength, including its impact on transfer length in prestressed members, is essential to safely incorporate SCC in modern applications. To foster this understanding, several American universities and State Departments of Transportation (DOTs) have recently sponsored projects to analyze the bond characteristics and transfer length of prestressing strands in SCC girders. Select data from these studies is presented herein, though a comprehensive summary may be found in a synthesis review executed by Andrawes et al. in 2009 [2]. As evidenced in the review, results are somewhat inconclusive. Studies by Ruiz et al. [3], Larson et al. [4], Hamilton and Labonte [5], and Trent [6] showed transfer lengths of strands in SCC to meet code provisions stipulated by both the American Concrete Institute (ACI) [7] and the American Association of State Highway Transportation Officials (AASHTO) [8]. Naito et al. [9] noted that strands in SCC met code requirements, though they did not satisfy minimum pullout loads suggested by Logan [10]. In contrast, studies by Zia et al. [11] and Girgis and Tuan [12] showed inadequate transfer lengths in SCC when compared to code provisions. Haq [13] and several of the aforementioned researchers observed via pull-out tests lower bond strength in SCC than in CC. Variations in mix constituents, strand types, and specimen types throughout the studies provide no constant by which to compare results. Furthermore, the large-scale nature of each study does not encourage iterative testing to eliminate inconsistencies. Thus, to augment previous research and explore the application of SCC in highway bridges, the U.S. Illinois DOT (IDOT) has sponsored its own study comprising, in part, the aforesaid synthesis review and the contents of this paper.

The paper at hand first examines results from eight large-scale projects that have published studies on SCC bond behavior pertaining to transfer length in prestressed members. The governing parameters in the studies are identified. The paper then utilizes experimental data from eight sets of pull-out tests conducted at the University of Illinois at Urbana-Champaign (UIUC) to derive bond stress–slip relationships for 12.7 mm steel strand embedded in SCC and CC. Modification factors are applied and the relationships are incorporated in finite element (FE) analyses to predict the transfer lengths of strands within a prestressed T-beam

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experimentally tested by Haq [13] and a box girder tested at UIUC. The predicted transfer lengths are compared to experimental results and current U.S. design standards.

2. Previous research synopsis

Eight large-scale projects within the United States have published studies on SCC bond behavior as it pertains to transfer length within prestressed members. Developing universal bond criteria from these studies is difficult given their range of test variables. Select data has been compiled in this article to provide brevity in contrasting previous research. Table 1 lists the constituents of the studies' SCC mixes and of an IDOT-approved SCC. The table shows high variability in the amount of air-entraining agent (AEA) and viscosity-modifying admixture (VMA) used in the SCCs. Of the 14 mixes, nine contained an AEA ranging from 70 to 861 mL/m^3 and half incorporated a VMA ranging from 482 to 5268 mL/m^3. The amount of VMA is particularly significant because it may adversely affect bond [12]. Several mixes included supplementary cementitious materials; both Hamilton and Labonte [5] and Girgis and Tuan [12] tested mixes containing fly ash, while Naito et al. [9] tested SCC containing blast furnace slag. External literature has documented the effect of these additives on plastic mix properties, though their impact on bond in hardened concrete remains unclear [14,15].

In the United States, each state is responsible for developing its own SCC mix guidelines, introducing myriad variables into SCC bond data. Using results from earlier studies to predict bond adequacy of a proposed SCC mix may be unsound when the studies' mixes do not comply with standards applicable to the proposed SCC. When compared to IDOT Bureau of Materials & Physical Research provisions for precast SCC, nine mixes in Table 1 exceed the maximum cement factor, eight exceed the limit for fine aggregate proportions, and three have water/cement ratios outside the current allowable range [16]. Noncompliance with IDOT standards prevents these mixes from serving as a basis for bond criteria in new Illinois SCC.

Table 2 contains, where available, the specimen types, concrete strengths, bond strengths, and transfer lengths reported in the eight aforementioned studies. Four studies entailed modified Moustafa pull-out tests to qualify the bond characteristics of strand in SCC as satisfactory when compared to the same strand in CC [17]. Columns six and seven of Table 2 list the absolute and normalized bond strengths as explicitly reported in the literature or as derived from available data. When bond strength was calculated using pull-out test data, the pullout load was assumed to be uniformly distributed along the embedded strands. The eighth column in Table 2 contains the experimental transfer lengths ($L_{t,\text{test}}$) from each study, and the final column compares them to AASHTO requirements ($L_{t,\text{code}}$), or a value 60 times the strand diameter [8]. In three studies, the ratio $L_{t,\text{test}}/L_{t,\text{code}}$ for at least one specimen series exceeded unity, indicating insufficient bond between strand and SCC. Physical test variables not listed in Table 2 may have also impacted test results and were not constant throughout the studies. For example, each study tested a different specimen type containing a unique number of strands, not all of which were bottom reinforcement; transfer lengths are known to vary between top and bottom strands [4].

After reviewing the previous studies, it could be concluded that although determining transfer length experimentally may be the most rigorous method for assessing bond strength of strands in SCC, the large number of material and geometric variables involved would make such a method impractical in terms of time and cost. Hence, a simple yet accurate analytical approach is needed to predict transfer length. The following sections propose a systematic way to predict transfer lengths in prestressed members using

Table 1
SCC mixes from eight US studies and typical illinois mix.

Reference		[4] Larson et al.	[6] Trent			[13] Haq		
Material	Units	SCC	S1CCM	S1CCM2	SCC1	SCC2A	SCC2B	SCC3
Cement	kg/m^3	444[a]	444[a]	441[a]	444[a]	415	415	415
Coarse agg.	kg/m^3	806	963	978	876	818	818	850
Fine agg.	kg/m^3	889	794	775	964	845	845	755
Fly ash	kg/m^3	–	–	–	–	–	–	–
Fine agg./total agg.		0.52[b]	0.45	0.44	0.52[b]	0.51[b]	0.51[b]	0.47
Water	L/m^3	134	168	168	153	163	163	183
W/C ratio		0.30[c]	0.38	0.38	0.35	0.39	0.39	0.44
AEA	mL/m^3	193	–	–	508	203	474	861
HRWR	mL/m^3	2708	–	–	3751	3950	3257	4162
VMA	mL/m^3	–	–	–	–	1893	482	4162
Set retardant	mL/m^3	–	–	–	20,307	–	15,858	12,636
Reference:		[5] Hamilton et al.	[9] Naito et al.	[3] Ruiz et al.	[12] Girgis & Tuan		[11] Zia et al.	Illinois
Material	Units	SCC	SCC	SCC	Mix #1	Mix #2	SCC	SCC
Cement	kg/m^3	446[a]	503[a,d]	563[a]	474[a]	374	480[a]	391
Coarse agg.	kg/m^3	774	978	800	760	777	788	917
Fine agg.	kg/m^3	838	760	873	840	859	770	857
Fly ash	kg/m^3	100	–	–	89	59	–	–
Fine agg./total agg.		0.52[b]	0.44	0.52[b]	0.53[b]	0.53[b]	0.49	0.48
Water	L/m^3	153	161	168	173	173	203	149
W/C ratio		0.34	0.32	0.30[c]	0.37	0.46[c]	0.42	0.38
AEA	mL/m^3	70	77	–	–	–	94	735
HRWR	mL/m^3	2491	5268	4042	542	542	3133	3094
VMA	mL/m^3	–	619	735	387	387	–	–
Set retardant	mL/m^3	534	–	–	193	193	1253	–

[a] Exceeds maximum cement factor of 418 kg/m^3.
[b] Water/cement ratio falls outside range of 0.32–0.44.
[c] Fine aggregate proportion exceeds maximum of 50% of total aggregate by weight.
[d] Mix also contains 25 kg/m^3 of slag.