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Michael Howland
University of Arkansas, Fayetteville

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On behalf of the

University of Arkansas

and the

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Michael B. Howland

presents his

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BOND PERFORMANCE OF LIGHTWEIGHT SELF-CONSOLIDATING CONCRETE

Michael B. Howland (1), Royce W. Floyd (2), and W. Micah Hale

(1) University of Arkansas, USA
(2) University of Arkansas, USA
(3) University of Arkansas, USA

Abstract

Self-consolidating concrete (SCC) allows for the placement of concrete without consolidation. The use of lightweight (LW) concrete reduces dead loads and lowers transportation costs. LWSCC is a recent combination of the two types of concrete; therefore there is little information on the performance of prestressed members cast with LWSCC. This project examines transfer length of LWSCC beams and compares the measured values to control-mixture members cast with normal weight SCC. Eight prestressed beams were cast. Of the eight, four conventional were cast with SCC and the remaining four with LWSCC. The lightweight mixtures contained expanded clay aggregate and had an approximate unit weight of 1880 kg/m^3. The control beams were cast with normal weight SCC and had an approximate unit weight of 2340 kg/m^3. The beams measured 16.5 cm x 30.5 cm x 5.5 m and contained two 15.2 mm-diameter seven-wire strands located 25cm from the extreme compression fiber. The one-day release strengths of the LWSCC beams averaged 30 MPa and the release strengths of the NWSCC beams averaged 33 MPa. The transfer (or transmission) length was measured for all beams, determined by measuring surface strains of the beam and measuring the end slip of the stand. The results were compared to standardized ACI 318 and AASHTO LRFD equations.

Keywords: Transfer length, bond, lightweight SCC

1. INTRODUCTION

Self-consolidating concrete (SCC) is a relatively new innovation in the concrete industry that allows for the placement of concrete without consolidation. The use of lightweight (LW) concrete reduces dead loads and lowers transportation costs. LWSCC is a recent combination of the two types of concrete. Because of this, there is little information on the performance of prestressed members cast with LWSCC. Comparison of past research suggests that there is similar bond behavior between LW and normal weight (NW) concrete. Additional research suggests that there is similar behavior between conventional concrete and SCC [1]. However, little research exists that pertains to bond strength of LWSCC; therefore, standardized bond equations used for analyzing conventional beams may not be adequate for LWSCC beams. Furthermore, there are little data that compares the measured transfer length (transmission length) values when using strand end slip or surface strain gages to quantifiably assess strand bond. This project estimates transfer length using two methods, surface gages and end slip, and compares measured values to those obtained using prediction equations.

2. BACKGROUND

2.1 Strand bond

Prestressed concrete relies on the bond between the strand and the concrete to transfer the stress from the steel to the concrete [2]. The distance over which the effective prestress applied to the strand is fully transferred to the concrete by means of bond in the end regions of the pretensioned members is referred to as the transfer length [3]. A long transfer length is not desired because the shear capacity within the transfer length is lower than in the rest of the member. If the shear capacity is too low due to an increased transfer length, the member may prematurely experience sudden shear failure [2]. This shear failure is the result of bond failure between the strand and concrete due to the reduced shear capacity within the transfer length. The bond within the transfer length is due primarily to the mechanical interlocking of cement paste with the irregular shape of the strand, and frictional forces due to the Hoyer effect, a wedging effect that occurs when the stress in the strand decreases near the end of the beam, thereby decreasing its axial strain and effectively increasing the strand diameter, due to Poisson’s ratio [4].

Because strand bond occurs internally within a concrete member, transfer length cannot be directly measured and must therefore be determined indirectly. Methods to measure transfer length include surface strain gage and strand end slip measurement. Standardized equations have also been developed to predict the transfer length (note: US Standard units). The American Concrete Institute (ACI) 318 Building Code Requirements for Structural Concrete [5] and the American Association of State Highway and Transportation Officials (AASHTO) LRFD Bridge Design Specifications [6] use the same basic expression, shown in Eq. (1), for transfer length, L_t:

$$L_t = \left(\frac{f_{se}}{3000}\right) d_b \tag{1}$$

In this expression f_{se} is the effective prestress in the strand after accounting for all losses (psi) and d_b is the nominal strand diameter (in.). Equation (2) shows the transfer length requirement mentioned in the AASHTO Specifications [5]:

$$L_t = 60d_b \tag{2}$$

Note that these equations do not account for LW concrete strengths or other bond characteristics.

2.2 Concrete

By definition, SCC is a highly workable concrete that compacts under its own weight yet has high resistance to segregation and does not bleed excessively. In order for concrete to qualify as SCC, it must adhere to the following criteria: a) flowability; b) passing ability; and c) resistance to segregation. The flowability and homogenous stability characteristics are accomplished by using more fine aggregates and using less or smaller coarse aggregate as well as using less water and substituting admixtures [2]. SCC is becoming increasingly popular in the industry because of its numerous benefits, including: a) increased placement time; b) reduced labor costs and noise pollution without need of mechanical vibration and compaction; and c) an improved finish when compared to conventional concrete.

LW concrete utilizes LW aggregates to achieve unit weights that range from 1685 kg/m^3 to 1925 kg/m^3. The use of LW concrete offers many industry benefits including reduced member dead loads, which can reduce transportation costs of precast members, and internal curing of the concrete due to the high absorption capacity of most LW aggregates, which can also increase the strength and durability of the concrete. There are, however, some drawbacks when using LW concrete, including reduced stiffness, increased cost due to using manufactured aggregate, difficulty in consistent batching due to the absorption capacity of the LW aggregates, and decreased shear capacity.

3. EXPERIMENTAL PROCEDURE

3.1 Beams

In this project, four prestressed LWSCC beam specimens with expanded clay aggregate and four prestressed NWSCC beam specimens with crushed limestone aggregate were cast. Each LWSCC beam and each NWSCC beam was cast with the same respective design mixture as presented in Table 1.

Table 1: Concrete Mixture Proportions

Material	LWSCC	NWSCC
Cement (kg/m^3)	490	461
Coarse Aggregate (kg/m^3)	386	837
Fine Aggregate (kg/m^3)	836	880
Water (kg/m^3)	196	184
w/c	0.4	0.4
HRWR (L/m^3)	6.1-7.9	6.8-10.6

The beam specimens measured 16.5 cm x 30.5 cm x 5.5 m and contained two 15.2 mm-diameter seven-wire Gr. 270 (1860 MPa) prestressing strands placed 5 cm on center and located 25 cm from the extreme compression fiber. These strands were pretensioned to 1400 MPa and gradually released at 24 hours. Due to the size of each beam specimen and the available lab equipment, each beam was cast using two batches of concrete (batch "a" and batch "b"). After each batch was produced, a series of fresh SCC property tests was run on the batch according to ASTM C1621, as presented in Table 2. Compressive strength tests, some results of which are presented in Table 2, were performed at 24 hours, 7 days, and 28 days.

Table 2: Fresh and Hardened Concrete Properties

		Fresh SCC Property Tests					Cylinder Strengths	
Batch	Unit Weight (kg/m^3)	Slump Flow (cm)	J-Ring Flow (cm)	J-Ring ΔH (cm)	T20 (s)	VSI	1-Day (MPa)	28-Day (MPa)
LW-1a	1849	69	58	5.5	5.4	0.0	27.7	33.9
LW-1b	1831	66	62	4.5	5.0	0.0	28.9	35.6
LW-2a	1917	67	61	3.0	4.0	0.0	31.9	42.3
LW-2b	1919	70	60	4.5	4.6	0.5	39.2	50.0
LW-3a	1868	71	65	4.0	3.2	0.5	26.3	35.8
LW-3b	1868	69	56	5.0	3.4	0.0	29.2	36.1
LW-4a	1865	66	62	4.0	4.4	0.0	27.3	37.4
LW-4b	1924	64	62	3.0	4.4	0.0	33.6	42.5
NW-1a	2315	48	42	5.5	4.6	0.0	36.3	46.0
NW-1b	2328	65	61	2.5	2.4	0.5	34.6	--
NW-2a	2356	67	62	4.5	2.8	1.0	38.6	55.0
NW-2b	2337	69	66	2.5	2.0	1.0	37.0	--
NW-3a	2355	67	61	4.0	3.2	1.0	29.2	54.0
NW-3b	2338	64	57	4.0	2.2	0.0	27.3	54.0
NW-4a	2342	64	57	4.0	2.8	0.5	28.4	53.7
NW-4b	2337	60	52	5.0	2.6	0.0	30.5	54.7

3.2 Instrumentation

3.2.1 Surface Strain Gages

Surface strain gage points were placed at the center of gravity of the prestressing strand at 10-cm increments along each side of the beam. The changes in distance between the gages were measured with a gage caliper just before strand release, just after release (at 24 hours), and at 3, 5, 7, 14, and 28 days after release. Two sets of measurements were taken at each reading to ensure accuracy. The transfer length was then determined using the 95% Average Maximum Strain Method [7].

3.2.2 End Slip

The transfer length was also determined by measuring the end slip of the strands. A small sheet of Plexiglas was affixed to the ends of the beam just above the strands to ensure a uniform, flat surface against which to take measurements. Fixed blocks were then placed approximately 5-7 cm from the end of the beam before the strands were released. The exact distance from the outside of the block to the Plexiglas on the ends of the beams was measured using a micrometer, as illustrated in Figure 1.

Figure 1: End Slip Measurement

This was done for each of the 4 strand-ends protruding from the beam just before strand release, just after release (at 24 hours) and at 3, 5, 7, 14, and 28 days. Two sets of measurements were taken at each reading to ensure accuracy. The transfer length was then determined using Eq. (3), the strand draw-in equation [2]:

$$L_t = 2\Delta_d \left(\frac{E_{ps}}{f_{si}}\right) \tag{3}$$

In this expression Δ_d is the measured end slip of the strand (cm), E_{ps} is the modulus of elasticity of the strand (MPa), and f_{si} is the tensile stress of the strand at release (MPa).

4. RESULTS

Surface strain and end slip data were recorded and analyzed from each beam specimen to determine transfer length. End slip data were analyzed using Eq. (3), the strand draw-in equation [2]. Surface strain data were analyzed using the 95% Average Maximum Strain method [7], as illustrated in Figure 2.

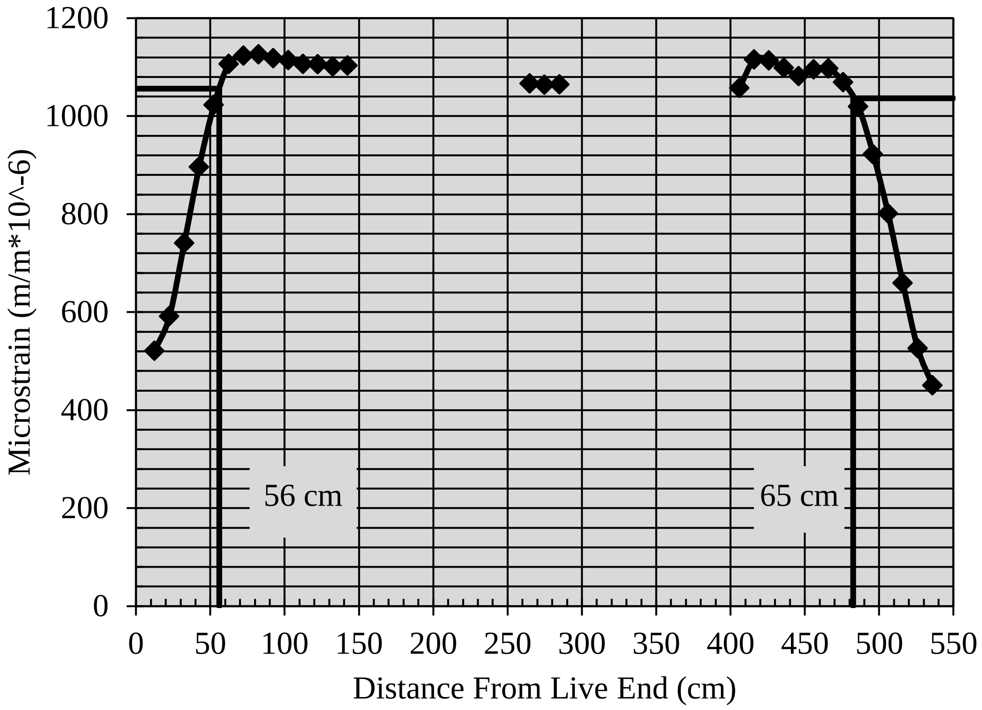

Figure 2: 28-Day Strain Profile for Specimen LWSCC-2

These analyses were performed for every beam specimen for each prescribed set of readings taken. Tables 3 and 4 report the composite live end and dead end transfer length values as well as the overall average value for each beam specimen for 1-day and 28-day data, respectively, and these values are compared to prediction Eqs. (1) and (2) [5,6].

Table 3: 1-Day Transfer Length Comparison

SCC Beam Specimen	Transfer Length (cm)							
	Surface Strain Gages			End Slip Measurements			Predicted Values	
	Live End	Dead End	Average	Live End	Dead End	Average	Eq. (1)	Eq. (2)
LW-1	81.0	49.0	65.0	43.6	21.6	32.6	88.9	91.4
LW-2	52.0	67.0	59.5	36.4	36.0	36.2	88.9	91.4
LW-3	73.0	52.0	62.5	60.6	23.2	41.9	88.9	91.4
LW-4	55.0	49.0	52.0	49.9	31.8	40.9	88.9	91.4
LW Ave.	**65.3**	**54.3**	**59.8**	**47.6**	**28.2**	**37.9**	-	-
NW-1	45.0	49.0	47.0	25.7	27.0	26.3	88.9	91.4
NW-2	44.0	47.0	45.5	23.0	22.7	22.8	88.9	91.4
NW-3	50.0	50.0	50.0	31.8	32.5	32.1	88.9	91.4
NW-4	50.0	99.0	74.5	32.4	101.8	67.1	88.9	91.4
NW Ave.	**47.3**	**61.3**	**54.3**	**28.2**	**46.0**	**37.1**	-	-

Table 4: 28-Day Transfer Length Comparison

SCC Beam Specimen	Transfer Length (cm)							
	Surface Strain Gages			End Slip Measurements			Predicted Values	
	Live End	Dead End	Average	Live End	Dead End	Average	Eq. (1)	Eq. (2)
LW-1	84.0	43.0	63.5	35.8	21.9	28.8	88.9	91.4
LW-2	56.0	65.0	60.5	34.5	40.2	37.3	88.9	91.4
LW-3	80.0	49.0	64.5	57.8	20.8	39.3	88.9	91.4
LW-4	59.0	73.0	66.0	47.9	30.6	39.2	88.9	91.4
LW Ave.	**69.8**	**57.5**	**63.6**	**44.0**	**28.4**	**36.2**	-	-
NW-1	58.0	59.0	58.5	42.3	41.4	41.9	88.9	91.4
NW-2	47.0	48.0	47.5	34.7	35.6	35.1	88.9	91.4
NW-3	58.0	59.0	58.5	47.9	46.2	47.1	88.9	91.4
NW-4	52.0	103.0	77.5	45.2	121.2	83.2	88.9	91.4
NW Ave.	**53.8**	**67.3**	**60.5**	**42.5**	**61.1**	**51.8**	-	-

Before a discussion of data analysis can occur, it is important to note the results of specimen NW-4. The dead end of this specimen suggests a much longer transfer length than other specimens in both Tables 3 and 4. This is likely due to poor consolidation caused by a time delay of concrete placement. Data from specimen NW-4 will be omitted from the discussion.

As seen in these data, transfer length increases over time caused by continual strand slip. This change tends to decrease over time and reaches a near constant value after 28 days. This suggests that the strand bond is highly dependent upon concrete strength and stiffness.

The surface strain data show that the average measured transfer lengths for each LW specimen are greater than each NW specimen. NWSCC exhibits slightly improved, yet similar, bond characteristics than LWSCC, which is expected due to the lower compressive strength and lower modulus of elasticity of LWSCC compared to NWSCC. At one day of age this same trend is present in the end slip data, although the data are not as consistent as those for surface strain. At 28 days, the differences between the average end slip and surface strain data in not as pronounced in the NWSCC specimens.

This raises the question of which method is more appropriate for determining transfer length. Surface strain is more accepted in research because it is regarded as the standard for measuring transfer length. Surface strain, however, requires time-consuming gage placement and measurement readings that are undesirable. End slip is much easier to measure than surface strain, saving time and money, and presents less chance for human error with fewer required measurements, but may not yield adequate results compared to surface strain. Therefore, a sufficient translation between the two methods is necessary so that transfer length can be determined with the ease of end slip measurements and the acceptance of surface strain measurements. This issue requires further examination.

Transfer length measurements from each method were compared to predicted values from Eqs. 1 and 2 [5,6]. These predicted values are conservative in each case. There is a certain amount of variability in the prestress transfer that must be accounted for. Sudden strand release will yield longer transfer lengths than those obtained in this project which were gradually released. Because of these factors, a certain amount of conservatism is necessary to prevent sudden bond and shear failures, which again are very undesirable.

5. CONCLUSIONS

- Based on the results of this project (excluding specimen NW-4), it is determined that LWSCC exhibits similar bond behavior to NWSCC. Due to lower concrete strength and modulus of elasticity of LWSCC compared to NWSCC, LWSCC has slightly longer transfer length than NWSCC.
- For either type of concrete, code prediction Eqs. 1 and 2 [5,6] are adequate for predicting conservative values for transfer length, which is necessary to account for variability in prestress transfer.
- In every case, transfer lengths determined by end slip were shorter than those determined by surface strain. End slip is a more desirable method to use than surface strain due to the ease of measurement, but there is still some question as to which method yields more accurate results. Future research will examine if end slip is adequate to determine transfer length through flexural testing of the eight beams.

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