STRAND BOND IN LIGHTWEIGHT SELF-CONSOLIDATING CONCRETE

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ABSTRACT

Presented in the paper are the results of a project that examined strand bond in lightweight, self-consolidating concrete (LWSCC) members. For the research project, eight prestressed beams containing two 0.60 in., Gr. 270 prestressing strands were cast. The beams measured 6.5 in. by 12 in. and were 18 feet in length. Four beams were cast with LWSCC while the remaining 4 beams were cast with normal weight self-consolidating concrete (SCC). The four LWSCC beams were cast with expanded clay. The unit weight of the lightweight mixtures was approximately 120 lb/ft^3 while the unit weight of the normal weight mixtures was approximately 145 lb/ft^3. Compressive strength for the LWSCC mixtures was approximately 4.4 ksi at release and 5.6 ksi at 28 days. Likewise, the release strength of the normal weight SCC mixtures was 4.7 ksi and the 28 days strength was 7.6 ksi. The preliminary results show that there was little difference in the development lengths for the beams. The development length for the LWSCC beams was between 48 and 50 in. The development length for the normal weight SCC beams was between 40 and 43 in.

Keywords: Light-weight, Self-Consolidating Concrete, Bond

INTRODUCTION

Beginning with Janney in 1954[1], strand bond has been a subject of much research. The equations that predict or estimate transfer and development length have come under much scrutiny. The applicability of these equations for all the various types of concrete has been questioned. This papers examines the applicability of the AASHTO LRFD and ACI 318 equations for transfer and development length for members cast with lightweight, self-consolidating concrete (LWSCC).

BACKGROUND

ACI Committee 213 defines lightweight structural concrete as "concrete having a minimum 28-day compressive strength of 2,500 psi, an equilibrium density between 70 and 120 lb/ft³, and consists entirely of lightweight aggregate or a combination of lightweight and normal density aggregate."[2] These unit weights are obtained by replacing the normal weight aggregate with lightweight aggregates such as expanded shales, slates, or clays.[2]

Lightweight concrete is popular in the precast/prestressed concrete industry. The lighter unit weights allow for longer spans and the possibility of reduced shipping costs.[3] Also, the reduced unit weights decrease dead loads which can reduce the costs associated with the foundation.[4]

The current ACI 318-08 Code provision for development length is expressed as

$$l_d = \left(\frac{f_{se}}{3000}\right) d_b + \left(\frac{f_{ps} - f_{se}}{1000}\right) d_b, \quad\quad\quad \text{Equation 1}$$

where f_{se} is the effective stress in the steel (after accounting for prestress losses), f_{ps} is the stress in the steel at nominal flexural strength, and d_b is the nominal diameter of the prestressing strand.[5] This expression is the same as the rearranged AASHTO LRFD Specifications provision except the AASHTO expression includes a 1.6 multiplier for pretensioned members with a depth greater than 24 in.[6] The ACI Code specifies a minimum transfer length of $50d_b$ for use in shear strength calculations[5] and AASHTO LRFD specifies a minimum transfer length of $60d_b$.[6] An expression for transfer length can be pulled out of the expression for development length and is taken as the first part of the expression

$$l_t = \frac{f_{se}}{3000} d_b \quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad \text{Equation 2}$$

with the remainder being the flexural bond length. The ACI code includes a modification for LWC that increases the required development length for deformed bars, but not for prestressing strand.[5]

Previous research results have been mixed regarding the applicability of these code equations to member cast with LWC. Some researchers have found the equations to be adequate while others have found the equations in need of modification.

MEYER AND KAHN

Meyers and Kahn examined the transfer and development length of six, prestressed AASHTO Type II cast with LWC. Their LWC was composed of expanded slate and had compressive strengths of 8790 and 11,010 psi. Each girder contained 10, 0.6 in. Gr. 270 stands. Transfer

lengths were determined using surface strain measurements. Average transfer lengths for the girders were 21.9 in. for the 8790 psi girders and 15.6 in. for the 11,010 psi girders. Based on their results, the authors stated that the current transfer length equations required no modification for the LWC used in their research program. The girders were then tested in flexure to estimate development length. They found that the current equations overestimated development length and were therefore conservative for their LWC.[7]

THATCHER ET AL

The authors developed LWC mixtures with targeted design strengths of 6,000 psi and 8,000 psi with equilibrium unit weights of 118 and 122 pcf, respectively. From these mixtures, five AASHTO Type I girders were cast with LWC (2 girders using 6,000 psi concrete and 3 using 8,000 psi concrete). A sixth girder was cast using 6,000 psi normal weight concrete (NWC). The Type I girders contained 12, 0.5 in. Gr. 270 prestressing strands. Using concrete surface strains, the authors determined the ACI and AASHTO transfer length equations were conservative for beams cast with NWC. However, they suggested that the ACI and AASHTO transfer length equations were not conservative for LWC beams. When the beams were tested in flexure, it was determined that the development lengths were similar for both NWC and LWC and also the ACI and AASHTO equations for development length were also conservative for both types of concrete mixtures used in their study.[8]

NASSAR

Nassar examined the feasibility of using high strength lightweight concrete (HSLWC) for bridges in Virginia. For their project, three AASHTO Type II girders and two AASHTO Type IV were cast. One Type II girder was cast with NWC that had a compressive strength of 7,800 psi. The remaining beams were cast with a HSLWC that had a 28 day compressive strength of 6,380 psi and a unit weight of approximately 114 pcf. The Type II girders contained 8, 0.5 in. strands, and the Type IV girders contained 38, 0.5 in. strands.[9]

The Type IV girders were used for transfer length measurements whereas the Type II girders were used for development length testing. Measured transfer lengths were less than those predicted using ACI and AASHTO equations. Even though the measured values were less than the predicted values, the authors recommend using $60d_b$ or $f_{si}d_b/3$ to predict transfer length.[9]

The authors state the ACI and AASHTO equations for development were adequate for developing the nominal moment capacity of HSLWC beams, but the suggest using a modification of 1/0.85 to increase development lengths until more testing is completed. They recommended additional development length testing on HSLWC members.[9]

PETERMAN ET AL

Peterman et al examined strand bond in semi-light weight beams. Eighteen rectangular and T-shaped beams were tested in flexure to determine development length. The concrete had a unit weight of approximately 130 pcf. Two concrete mixtures were used. A 7,000 psi mixture was used with ½ in. special strand, and a 10,000 psi mixture was used with 0.6 in. strand. The beams

were tested to failure to estimate development length. Based on the results of single strand specimens, the AASHTO development length equation was adequate. In multiple strand T-beams, flexure-shear cracks led to bond failure in some of the beams. Additional T-beams were cast with reduced stirrup spacing which resulted in flexure failures. Without the problems associated with flexure-shear cracking which is due to the lower modulus of rupture of semi-light weight beams that makes them more susceptible to cracking, the researchers suggest the current AASHTO equation for development length is conservative for semi-light weight concrete. The author further recommended that "the current requirements for strand development lengths should be enforced at a critical section that is located a distance d_p from the point of maximum moment toward the free end of the strand, where d_p is the distance from the extreme compression fiber to the centroid of the prestressed reinforcement."[10]

WARD ET AL

Ward et al examined the bond (transfer and development length) of 0.5 in. strand cast in lightweight self-consolidating concrete (LWSCC).   Six prestressed beams measuring 6.5 in. by 12 in. by 18 ft. were cast. The beams had an average one day compressive strength of 4,530 psi and 28 day strength of 6,700 psi. The average unit weight was 119 lb/ft^3 (1910 kg/m^3). Transfer length was measured using surface strains and development length was evaluated through flexural tests. The average transfer length was 17. 5 in. (dead end) and 22.3 in. (live end). The development length was determined to be less than 30 in. Both values were less than those predicted by ACI and AASHTO.[11]

SCOPE

The goal of the research program was to investigate strand bond in LWSCC. To accomplish this, eight prestressed beams were cast. Four of the beams were cast with LWSCC, and four beams were cast with normal weight SCC (NWSCC). The beams measured 6.5 in. by 12 in. by 18 ft. in length.   The beams contained two 0.60 in., Gr. 270 strands located 10 in. from the extreme compression fiber and two, No. 6, Gr. 60 rebar located two (2) inches from the extreme compression fiber. Shear reinforcement consisted of Gr. 60, 0.25 in. stirrups spaced at 5 in. throughout the length of the beams. A cross-section of the beam is shown in Fig. 1 and photographs of the beams are shown in Fig. 2. As seen in Fig. 2, the first specimens cast had some discoloration which was due to the formwork. The beam forms were lined with plastic for the remaining specimens which can be seen in Fig. 3.

The LWSCC and NWSCC mixtures used to cast the beams are shown below in Table 1. Both mixtures contained the same Type I portland, fine aggregate which consisted of river sand, and a high range water reducer (HRWR). The HRWR was classified as an ASTM C494 Type A and F and ASTM C1017 high range water reducer. The only difference between the mixtures was coarse aggregate. The NWSCC contained ½ in. limestone while the LWSCC contained ½ in. expanded clay.
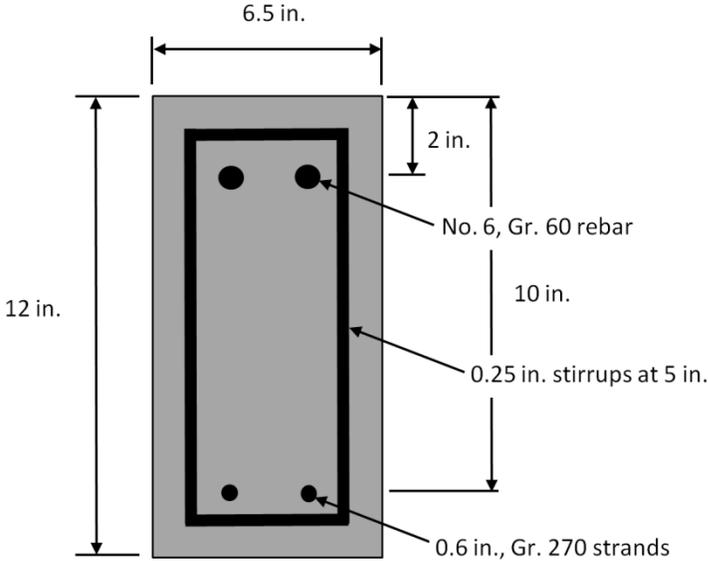
Fig. 1 Cross-section of Beam Specimens.

Fig. 2 Photograph of Specimens.

Fig. 3 Specimen Casting.

Table 1. Concrete Mixture Proportions.

Material (lb/yd^3)	LWSCC	NWSCC
Cement	825	775
Coarse Aggregate	649	1408
Fine Aggregate	1407	1481
Water	329	310
w/c	0.40	0.40
HRWR (fl oz/cwt)	5.0 – 6.5	4.5 – 7.0

Due to the limited mixer capacity, two batches of concrete were required to cast each beam. Each batch of concrete was transported from the mixer to the formwork in the front end loader of a tractor. The concrete was placed without vibration and each beam was cast in approximately 45 minutes.

The morning the beams were cast, the strands were tensioned to 202.5 ksi ($0.75f_{pu}$). After 18 hours, detachable mechanical strain gages (DEMEC) points were affixed to the beams at the center of gravity of the prestressing strands. The DEMEC points were placed at 4 in. intervals for the first 60 in. from the beam ends and for 16 in. at midspan (Fig. 4). The surface strains were measured prior to strand release. At approximately 24 hours after casting, the strands were gradually released by relieving the pressure simultaneously in each of the hydraulic rams used to tension the strands. Immediately after release, the surface strains were measured once again.

Fig. 4 DEMEC Points Affixed to a Beam.

STRAND QUALITY

The standard test for strand bond (STSB) was used to assess strand quality.[13] Six strand samples were tested. Mortar flow, compressive strength, and load at 0.10 in. of movement on the dead end of the strand are reported in Table 2 and photograph of the test is shown in Fig. 5. Due to the required amount mortar, it was necessary to mix two separate mortar batches. The average STSB value for the six samples was 19,180 lbf which was greater than the 12,600 lbf minimum value reported in NCHRP Report 603.[13] Unfortunately, the compressive strength of both mortars exceeded the specifications by approximately 300 psi and the results cannot be used to compare to a threshold value.

Fig. 5 STSB Test.

Table 2. STSB Results.

Properties – Mortar Batch 1	Strand 1
Mortar Flow (%)	111.9
Beginning Mortar Strength (psi)	5070
Pull-Out Force (lbf) – Sample 1	18010
Pull-Out Force (lbf) – Sample 2	19340
Pull-Out Force (lbf) – Sample 3	16170
Ending Mortar Strength (psi)	5270
Properties – Mortar Batch 2	Strand 1
Mortar Flow (%)	99.8
Beginning Mortar Strength (psi)	5070
Pull- Out Force (lbf) – Sample 4	18540
Pull- Out Force (lbf) – Sample 5	21010
Pull- Out Force (lbf) – Sample 6	22020
Ending Mortar Strength (psi)	5210

CONCRETE PROPERTIES

The fresh and hardened concrete properties of the LWSCC and NWSCC are shown below in Table 3. The average fresh concrete properties for the LWSCC and NWSCC mixtures were similar. The slump flow for the LWSCC was 26.6 in. with a T-20 of 4.3 seconds. Likewise, the slump flow and T-20 for the NWSCC was 24.8 in. and 2.6 seconds, respectively. Shown in Fig. 6 is a typical slump flow for the LWSCC.

The average one day compressive strengths (f'_{ci}) for the two mixtures were within 330 psi of each other. However, the same cannot be said for the 28 day strengths (f'_c). There was approximately 2000 psi difference between the NWSCC and LWSCC. This difference can be attributed to the lightweight aggregate which was not as strong as the limestone and therefore limited the maximum compressive strength of the LWSCC.

Fig. 6 Typical Slump Flow for LWSCC.

Table 3. Concrete Properties.

Specimen	Slump Flow (in.)	T_{20} (sec)	VSI	J-Ring Flow (in.)	J-Ring Δ (in.)	f'_{ci} (psi)	f'_c (psi)
LWSCC-1	27.0	5.4	0.0	23.0	4.0	4010	4910
	26.0	5.0	0.0	24.5	1.5	4190	5160
LWSCC-2	26.5	4.0	0.0	24.0	2.5	4630	6140
	27.5	4.6	0.5	23.5	4.0	5680	7250
LWSCC-3	28.0	3.4	0.5	25.5	2.5	3810	5200
	27.0	3.4	0.0	22.0	5.0	4230	5240
LWSCC-4	26.0	4.4	0.0	24.5	1.5	3960	5430
	25.0	4.4	0.0	24.5	0.5	4870	6170
Average	**26.6**	**4.3**	**0.1**	**23.9**	**2.7**	**4420**	**5690**
NWSCC-1	19.0	--	0.0	16.5	2.5	5260	6670
	25.5	2.4	0.5	24.0	1.5	5010	6750
NWSCC-2	26.5	2.8	1.0	24.5	2.0	5600	7970
	27.0	2.0	1.0	26.0	1.0	5360	--
NWSCC-3	26.5	3.2	1.0	24.0	2.5	4240	7840
	25.0	2.2	0.0	22.5	2.5	3960	7840
NWSCC-4	25.0	2.8	0.5	22.5	2.5	4110	7780
	23.5	2.6	0.0	20.5	3.0	4420	7930
Average	**24.8**	**2.6**	**0.5**	**22.6**	**2.2**	**4750**	**7540**

RESULTS – TRANSFER LENGTH

The transfer lengths were determined by examining the surface strain profiles of the beams. Once the strain data was obtained, the 95% AMS method was used to determine the transfer length for each beam end.[12] In this method, strain readings are averaged with adjacent points and plotted creating a smoothed-strain profile. Using the smoothed-strain profile, the values within the strain plateau were averaged to determine the average maximum strain (AMS). The AMS was multiplied by 0.95 and a line was drawn using this value. The transfer length was determined by locating the intersection of the 95% AMS line and the smoothed-strain profile. This process is shown for LWSCC-2 in Fig. 7 below.

The measured transfer lengths for the dead and live ends at 28 days of age are shown below in Table 4. Also shown in Table 4 are the predicted transfer lengths using $50d_b$, $60d_b$, and Equation 2. The effective stress in the steel after all losses (f_{se}) was determined from previous research that measured prestress losses in beams of the same size. The value of f_{se} used in the calculations was 178.3 ksi.[13]

The results show that the current ACI and AASHTO code equations are applicable to LWSCC. Measured transfer lengths for both types of concrete were less than all predicted values except for the dead ends of LWSCC-1 and LWSCC 2 and the live end of NWSCC-4. NWSCC 4 was not self-consolidating which was due to high ambient temperatures that increased slump loss. The finished beam displayed a poor surface appearance and had bugholes throughout the length of the beam. The bugholes and poor consolidation around the strands reduced bond and therefore increased transfer lengths.

For the dead ends of LWSCC 1 and 2, the measured values exceeded $50d_b$. There is a possibility that this could be due to compressive strength. These two beams had on average the lowest compressive strength at release and at 28 days. However this does not explain why the live end transfer lengths were significantly shorter even though the same concrete mixture was used to cast the beams.
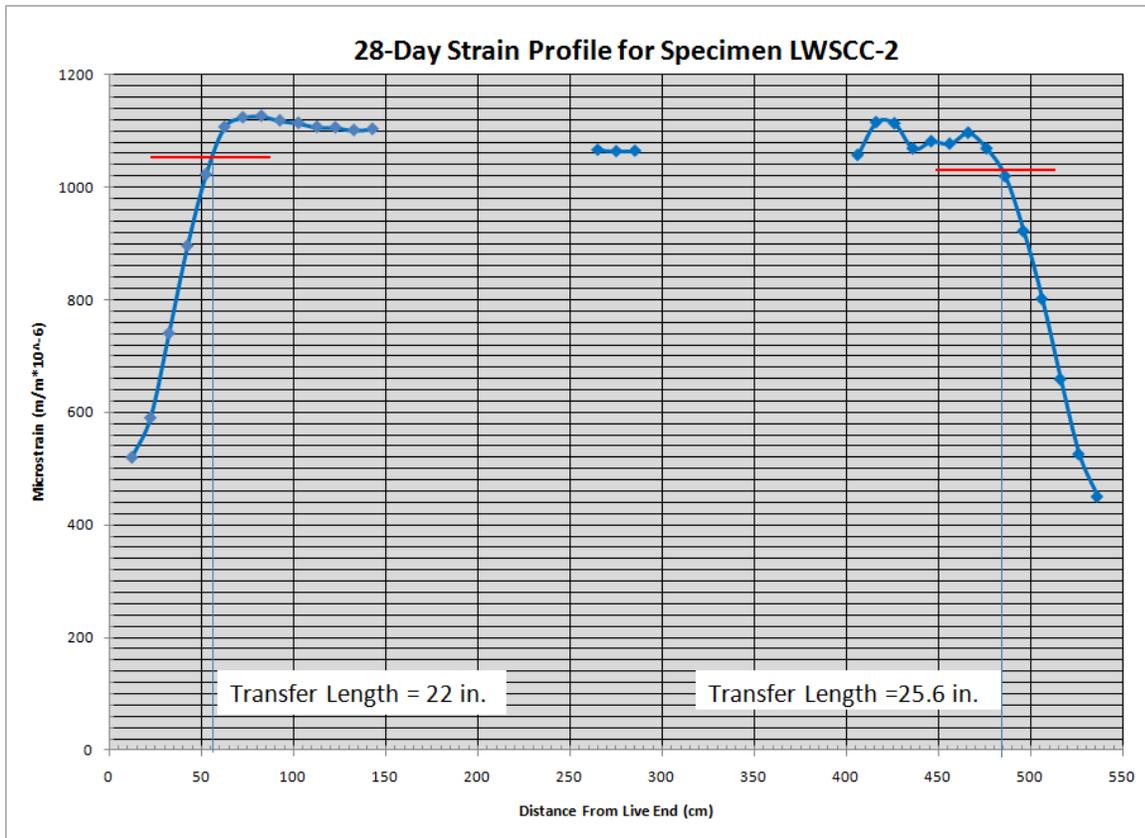
Fig. 7 Strain Profile for LWSCC-2.

Table 4. Transfer Length Results.

Specimen	Transfer Length				
	Dead End (in.)	Live End (in.)	$50d_b$ (in.)	$60d_b$ (in.)	$(f_{se}/3)d_b$ (in.)
LWSCC-1	33.1	16.9	30	36	35.6
LWSCC-2	22.0	25.6	30	36	35.6
LWSCC-3	31.5	19.3	30	36	35.6
LWSCC-4	23.2	25.2	30	36	35.6
Average	**27.5**	**21.8**	**-**	**-**	**-**
NWSCC-1	22.8	24.4	30	36	35.6
NWSCC-2	18.5	18.9	30	36	35.6
NWSCC-3	22.8	23.2	30	36	35.6
NWSCC-4[1]	20.5	40.6	30	36	35.6
Average	**21.2**	**26.8**	**-**	**-**	**-**

1. NWSCC was poorly consolidated.

RESULTS – DEVELOPMENT LENGTH

Development length was determined through flexure tests on each end of the eight beams. The strands were instrumented with linear voltage displacement transducers (LVDT) to monitor strand slip during testing. Determination of development length was an iterative process. At a given strand embedment length, L_E, if the strand slipped and the beam failed before the nominal moment capacity was achieved, the development length was greater than the embedment length. Likewise, if the beam achieved its nominal moment capacity with no strand slip, the development length was less than the embedment length. Shown in Fig. 8 is a schematic of the test set-up. The results from the development tests are shown below in Table 5.

The predicted development lengths are also shown in Table 5. These values are calculated using Equation 1. As previously mentioned, the value for f_{se} (178.3 ksi) was determined for similar beams in a previous research program. Likewise, the value for f_{ps} was assumed to be 266 ksi for all beams based on prior research.[13]

Like the transfer length results, the NWSCC beams had a shorter development length than the LWSCC beams. Both beams had development lengths shorter than the code predicted value of 88.3 in. The results also show how important consolidation is for achieving sufficient bond. NWSCC-4 which was not self-consolidating experienced strand slip at an embedment length of 56 in. which is approximately 30% greater than the average development length measured for the truly self-consolidating NWSCC beams.
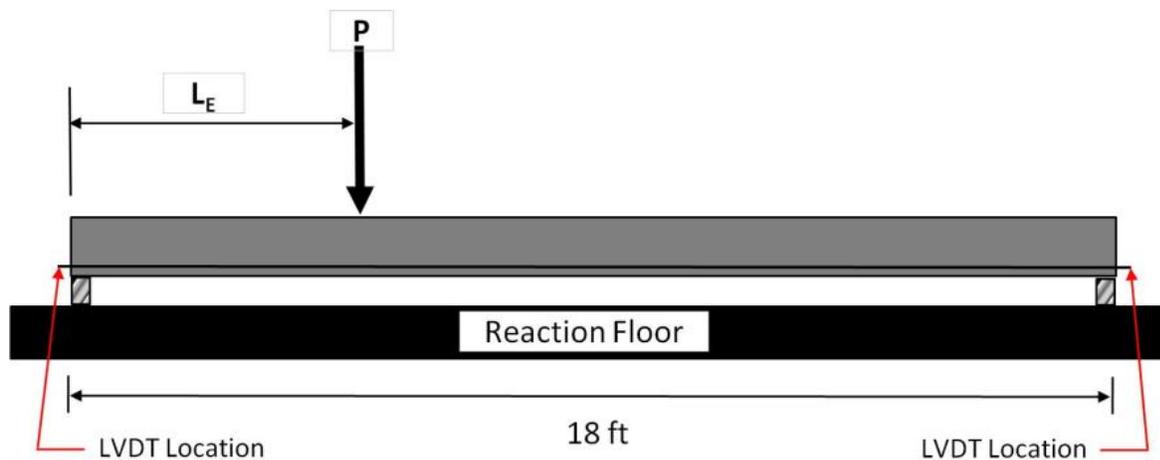

Fig. 8 Schematic of Development Length Test.

Table 5. Development Length Results.

Beam	L_E[1] (in.)	Slip	Failure Type
LWSCC1 - L	45	yes	slip/shear
LWSCC1 - D	50	no	yielding and concrete crushing
LWSCC2 - L	55	no	yielding and concrete crushing
LWSCC2 - D	52	no	yielding and concrete crushing
LWSCC3 - L	48	yes	shear
LWSCC3 - D	52	yes	shear/slip
LWSCC4 - L	60	no	yielding and concrete crushing
LWSCC4 - D	48	yes	yielding and concrete crushing, one shear crack
Measured $48 < l_d < 50$ in. for LWSCC			
Predicted $l_d = 88.3$ in. for LWSCC			
NWSCC1 - L	40	yes	slip/flexure
NWSCC1 - D	37	yes	shear
NWSCC2 - L	43	no	yielding and concrete crushing
NWSCC2 - D	40	--	yielding and concrete crushing
NWSCC3 - L	34	yes	slip/concrete crushing
NWSCC3 - D	40	yes	shear/slip/concrete crushing
NWSCC4 - L*	47	no	yielding and concrete crushing
NWSCC4 - D*	56	yes	shear/slip
Measured $40 < l_d < 43$ in. for NWSCC			
Predicted $l_d = 88.3$ in. for NWSCC			

1. Embedment length
L = denotes live end of beam
D = denotes dead end of beam
* = NWSCC4 was poorly consolidated

CONCLUSIONS

The goal of the research program was to examine the transfer and development length of prestressed concrete members cast with LWSCC. Eight beams were cast; four beams were cast with LWSCC and four beams were cast with NWSCC. The beams had approximately the same compressive strength at release; however, the NWSCC had 28 day strengths approximately 2000 psi greater. Based on the research results and the mixtures included in the research, current code equations for transfer and development length are applicable for LWSCC members. For the concrete mixtures and specimens examined in this study, the following conclusions can be made from the research program.

- The compressive strength of lightweight concrete mixtures can be limited by the strength of the lightweight aggregate.
- Proper consolidation is essential for good bond. Specimen NWSCC-4 was not self-consolidating and had a transfer length that exceeded both ACI and AASHTO code equations. The development length of NSWCC-4 was the largest of all tested specimens.

- There was little difference in transfer length between the NWSCC and LWSCC members. The code equations were conservative for both types of concrete.
- The development length results show that the NWSCC may provide marginally better bond than LWSCC.
- Current code equations for development length are applicable for members cast with LWSCC.

ACKNOWLEDGMENTS

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