BOND OF 0.5 in. DIAMETER STRANDS CAST IN LIGHTWEIGHT SCC

Dustin B. Ward, EI, B & F Engineering, Inc., Hot Springs, AR
Royce W. Floyd, EI, Research Assistant, University of Arkansas, Fayetteville, AR
W. Micah Hale, PE, Associate Professor, University of Arkansas, Fayetteville, AR

ABSTRACT

This paper presents the bond properties of 0.50 in. prestressing strand cast in light weight self-consolidating concrete (LWSCC). Six beams containing two 0.50 in. strands were cast in the laboratory. Various tests were performed on both the material properties of the LWSCC and the performance of the LWSCC beams. The measured fresh properties included slump flow, T_{20}, and J-Ring. For the six beams the slump flows averaged 22 in. with T_{20} times of 6 seconds. The average unit weight of the mixtures used to cast the beams was 119 lb/ft^3. Hardened properties of the concrete, including compressive strength and modulus of elasticity, were also evaluated. The compressive strength at release and at 28 days was 4530 psi and 6700 psi, respectively. Likewise, the measured modulus of elasticity at release and 28 days was 2300 and 3200 ksi, respectively. Additionally, the transfer and development length for the beams were measured. Transfer lengths were measured by evaluating the surface strains before and after strand release (and periodically afterwards). The beams were tested to failure to assess development lengths. The average measured transfer length was 20 inches and the development lengths ranged 25 to 30 inches. The measured values were then compared to those obtained using standard prediction equations.

Keywords: Lightweight SCC, Bond, Development Length

INTRODUCTION

Self-consolidating concrete (SCC) was originally developed at the University of Tokyo, Japan, in the 1980s. SCC has many advantages over conventional concrete, including easy placement in thin-walled elements and the ability to compact itself under its own weight without vibration.[1] There may also be a cost savings benefit due to the reduced amount of labor and equipment needed because of the ease of placement. Another benefit is reduced noise and vibration during placement.[2]

SCC is produced with readily available materials. Although essentially the same components are used for SCC as for conventional concrete, the mixture proportions vary somewhat. SCC uses a larger amount of fine aggregate while incorporating a smaller amount of coarse aggregates. SCC may also use more filler materials such as "fly ash, limestone powder, blast furnace slag, silica fume and quartzite powder.[1]" SCC has a low water to cementituous material ratio (w/cm), but it has a high degree of flowability. Typically, the w/cm for SCC is less than 0.40. The combination of low w/cm and flowability is due to the high range water reducers (HRWR) incorporated into the mix. Typically, the dosage rate of HRWR ranges from 0.5% to 2.0% of the weight of the cement in the mix.[2]

SCC can be pumped through an opening in the bottom of forms, or it can be conventionally placed from the top of forms. Tests on SCC have proven it to be fairly homogeneous. SCC has an additional advantage in that it moves through intricate formwork without segregation or bleeding.[2] These benefits make SCC very appealing to the precast/prestressed concrete industry.

BACKGROUND

Beginning with Janney's research in the 1950's, several researchers have examined the bond of the prestressing strand in conventional and high strength concrete.[3] Recently, numerous researchers have examined the bond of strand cast in SCC. Larson et al. concluded that the current equations for development length were adequate for the SCC mixture and beam geometries he examined.[4] Hegger et al. examined the bond strength and shear capacity of SCC members. Hegger et al. observed that the current calculations for transfer length are valid for SCC mixtures as they contain adequate safety margins.[5] Recently precasters are using lightweight SCC (LWSCC) to reduce shipping costs and to benefit from the advantages of SCC previously mentioned. However, there is little published data on the performance of precast members cast with LWSCC. This paper presents the results of a study that examined the transfer and development of prestressed beams cast with LWSCC.

ACI 318-08 defines transfer length as the "length of embedded pretensioned strand required to transfer the effective prestress to the concrete."[6] Transfer length is estimated using ACI and AASHTO codes based on the effective stress and the strand diameter. Other variables affecting transfer length are "type of steel (wire or strand), size of the steel (diameter), steel stress level, surface condition of steel (bright, rusty, or epoxy coated), concrete strength, type of release (gradual release or sudden release by flame cutting the strands), time-dependent effects, and debonded strands."[7] Development length describes the "length of embedded reinforcement, including pretensioned strand, required to develop the design strength of reinforcement at a critical section."[6] ACI 318-08 provides a formula for calculating development length of a prestressing strand. This formula is:

$$l_d = \left(\frac{f_{se}}{3000}\right)d_b + \left(\frac{f_{ps} - f_{se}}{1000}\right)d_b$$

where:
l_d is the development length, in
f_{se} is the effective stress in prestressing, psi
f_{ps} is the stress in prestressing steel at nominal flexural strength, psi
d_b is the nominal diameter of the prestressing strand, in.

The first term in the equation represents the estimated transfer length, and the second term represents the flexural bond length.[7, 8]

EXPERIMENTAL PROGRAM

The research program consisted of casting 6 beams with a LWSCC mixture. The transfer length and development length of the strands for each beam was measured. The beams had cross sectional dimensions of 6.5 inches x 12 inches and were 18 feet long. Each beam contained two 0.5 inch diameter Grade 270 seven-wire prestressing strands located at a depth of 10 inches. The center to center spacing of the strands was 2 inches, and there was 2 inches of clear cover on each side of the strands. Additionally, two #6 bars were placed 1.5 inches below the top surface of the beams. Shear reinforcement consisted of smooth 1/4 inch bars bent into stirrups spaced at 5 inches.

Materials

The same constituent materials and mixture proportion were used in all the beams. The concrete mixtures contained Type I cement, and the fine aggregate was washed river sand**.** The lightweight aggregate was expanded clay with a nominal maximum size of ½ inch. Also, the absorption capacity and specific gravity of the expanded clay was 24.1% and 1.30, respectively. The mixture proportion for the LWSCC is shown below in Table 1.

Table 1. LWSCC Mixture Proportion

Material	Quantity (lb/yd^3)
Cement	795
Water	302
Lightweight Aggregate	743
Fine Aggregate	1292
Calculated Unit Weight	116[1]

1. Unit weight units are lb/ft^3

Mixing and Placing

The LWSCC was mixed in a 9 ft^3 capacity rotary drum mixer. Two 7 ft^3 batches were mixed for each beam. The concrete was transported in wheelbarrows a short distance before being placed in the forms. Fresh concrete properties were measured and companion cylinders were made at the time of placement. Mixing of the second batch of concrete began after emptying the mixer of the first batch. Concrete was placed at one end of the beam and was allowed to flow to the opposite end. No vibration was used to consolidate the concrete into the forms. Hand trowels were used to smooth the top surface of the beams. A tarp was placed over the beams soon after placement to prevent rapid moisture loss. Shown below in Fig. 1 is a beam prior to concrete placement.

Fig. 1 Beam form and reinforcement cage before concrete placement

Transfer Length Measurements

Approximately 18 hours after placement, the tarp and the sidewalls of the forms were removed. A chalk line was used to mark the center of gravity (c.g.s.) of the strands. DEMEC targets were placed along each side of each beam along the c.g.s. of the strand. The DEMEC targets were affixed to the beams at a spacing of 4 inches. A DEMEC gauge was used to measure the change in length between the target locations. DEMEC readings were made before the strands were released (gradual release), immediately after transfer, and at 5, 7, 14, and 28 days after placement of the concrete. Since DEMEC readings were obtained from both sides of each beam, an average strain profile was developed. To determine transfer lengths, the averaged strain profiles were refined using the 95% average maximum strain method.[8] A photograph of the DEMEC gauge is shown below in Fig. 2.

Fig. 2 DEMEC Target Strain Gauge

Development Length

To determine development length, the six beams were tested. The beams were loaded to failure using a single concentrated load. The location of the concentrated load varied for each beam. Applied load, beam deflection, and strand end slip were measured for each beam. Linear variable displacement transducers (LVDTs) were attached to the strands extending from the end of the each beam. The LVDTs were able to detect small amounts of strand movement (strand slip) relative to the end of the beam.

As previously stated, the development length was determined by testing the beams to failure with the location of the load changing for each beam. The location of the load was based on the embedment length, L_E (Fig, 3). The embedment length is defined as the distance from the end of the beam to the section that can develop its full strength when the load is applied. Varied embedment lengths are used to establish bounds for the development length. The behavior of the strands at failure is used to determine whether the tested embedment length is longer or shorter than the development length. If strand slip occurs before the nominal moment is reached, then the embedment length is shorter than the development length and a longer embedment length is used for the next test. Conversely, if no strand slip is detected after the beam achieves the nominal moment, the embedment length is greater than the development length and a shorter embedment length is used for the next test. For the case where the embedment length is equal to the development length, failure by flexure occurs at the same time as strand slip after the nominal moment is reached. A photograph of a tested beam is shown below in Fig. 4.

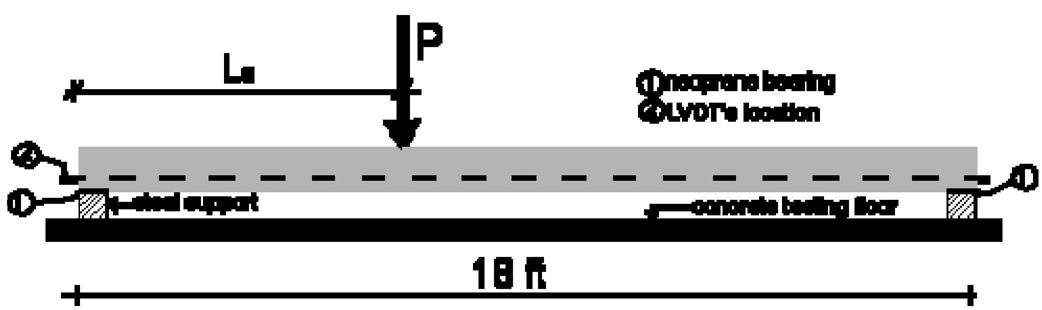

Fig. 3 Development length test set-up

Fig. 4 Instrumented beam after failure

RESULTS

Fresh Concrete Properties

Table 2 lists the measured fresh properties of the LWSCC used in the beams. As shown in Table 2, each mixture has an "a" component and a "b" component. These correspond to the two batches used to cast each beam. The slump flows observed were less than the targeted values of 24 to 26 inches. There are a few factors that could lead to slump flows lower than the target values. The most likely explanation is a difference between estimated moisture content and actual moisture content. Moisture content of the lightweight aggregate was estimated by measuring bulk loose density. A relationship between measured moisture content and bulk loose density was then used to estimate the moisture content of the lightweight aggregate. The tendency of lightweight aggregate to rapidly absorb or lose moisture required estimation of moisture content instead of obtaining a sample several hours in advance of batching and measuring the moisture content of a portion of the sample. Even though the slump flows were less than the targeted values, all beams had a smooth surface and did not require any vibration.

Table 2 Fresh Concrete Properties

Mixture	Slump Flow (in)	J-Ring Flow (in)	T_{20} (s)	T_{MAX} (s)	VSI	Unit Wt (lb/ft^3)
LWSCC 1a	23.00	-----	6.40	14.40	0.5	113.2
LWSCC 1b	22.00	-----	4.28	7.21	0.5	116.2
LWSCC 2a	21.50	17.50	4.11	9.52	0.5	116.8
LWSCC 2b	24.50	22.75	4.37	11.90	1.0	118.5
LWSCC 3a	19.00	-----	-----	11.00	0.5	117.8
LWSCC 3b	23.50	19.50	6.23	10.72	0.5	119.2
LWSCC 4a	22.75	18.50	6.45	12.11	1.0	120.4
LWSCC 4b	24.00	25.50	6.48	12.62	1.5	122.2
LWSCC 5a	20.75	-----	9.24	16.04	0.5	117.8
LWSCC 5b	20.00	19.25	7.21	13.56	1.0	121.0
LWSCC 6a	22.50	18.25	5.24	12.75	1.0	120.7
LWSCC 6b	20.00	18.25	6.51	15.01	1.0	124.0
Averages	22.0	20.0	6.05	12.24	0.5 - 1.0	119.0

Hardened Concrete Properties

As previously stated, due to mixer size, two batches, “a” and “b”, were used to cast each beam. The strength values reported in Table 3 are from cylinders cast from batch “a” and batch “b”. For quality control purposes, a limited number of cylinders were cast from batch “b” and were tested at 1 day and when the beams were tested. Cylinders from batch “a” were also tested at 7 and 28 days of age. Also shown in Table 3 are the compressive strength results for the Companion Batch. The Companion Batch consisted of the same mixture proportion of the beams (Table 1) and was used to measure the modulus of elasticity of the LWSCC.

The modulus of elasticity (MOE) of the Companion Batch is shown in Table 4. The measured modulus of elasticity was compared against prediction equations found in ACI 318-08.[6] The equation is shown below.

$$E_c = w_c^{1.5} 33\sqrt{f'_c}$$

where:
E_c = concrete modulus of elasticity (psi)
w_c = unit weight of concrete (lb/ft3)
f'_c = specified concrete compressive strength (psi)

Previous research has noted a tendency of normal weight SCC to exhibit MOE values lower than those of conventionally vibrated high performance concrete (HPC) of the same compressive strength. Gross et al. reported that the SCC in their research exhibited a 22% lower elastic modulus than high strength concrete of the same compressive strength.[10] Similarly, Holschemacher and Klug reported that the modulus of elasticity of SCC may be 20% lower than the modulus of elasticity of normally vibrated concrete having the same compressive strength.[1] These differences in elastic modulus have been attributed to the unique mixture composition of SCC. SCC typically contains a higher volume of cement paste and a lower volume of coarse aggregate than conventional concrete mixtures. Based on tests performed on the Companion Batch, the prediction equations overestimated the MOE of the LWSCC mixture from 9 to 17%.

Table 3. Compressive Strength Results (psi)

Mixture	1-day	7-day	14-day	28-day	f_c at l_d Tests[1]
LWSCC #1a	4480	5730	------	6790	6850
LWSCC #1b	4140	------	------	------	5780
LWSCC #2a	3780	5180	------	5920	6330
LWSCC #2b	5690	------	------	------	7780
LWSCC #3a	4390	6530	7080	7240	------
LWSCC #3b	4020	------	------	------	7510
LWSCC #4a	4010	6990	7510	6170	------
LWSCC #4b	2980	------	------	------	6910
LWSCC #5a	5260	5190	5500	6370	------
LWSCC #5b	5240	------	------	------	7420
LWSCC #6a	4860	7000	7020	7480	------
LWSCC #6b	5920	------	------	------	8310
Companion Batch	4100	5760	7230	6930	------
Average	4530	6060	6870	6700	7110

1. Concrete compressive strength at the time of beam tests.

Table 4. Modulus of Elasticity of the Companion Batch

Age (days)	f'_c (psi)	Measured MOE (ksi)	Predicted MOE (ksi)	Predicted/ Measured
1	4100	2300	2700	1.17
7	5760	2900	3200	1.10
28	6930	3200	3500	1.09

Transfer Length

The results of the transfer length measurements are shown in Table 5. The average measured transfer lengths ranged from 17.5 inches to 22.3 inches. Table 6 shows the predicted values of transfer length (using $l_t = (f_{se}/3)d_b$) and the measured live and dead end transfer lengths. Also shown in Table 6 is the effective prestress force, f_{se}. This value was calculated by subtracting the seating losses and elastic shortening losses from the initial prestress force of 202.5 ksi. The predicted transfer lengths ranged from 27.9 inches to 29.3 inches. All of the predicted values overestimated transfer length at 28 days. On average, predicted values were approximately 40 percent higher than measured values.

Table 5 Summary of Measured Transfer Length Results

Beam	Release		14-days		28-days	
	Live End	Dead End	Live End	Dead End	Live End	Dead End
LWSCC #1	15	21	-----	-----	23	25
LWSCC #2	17	24	-----	-----	18	13
LWSCC #3	24	19	27	15	27	15
LWSCC #4	21	33	20	19	20	27
LWSCC #5	17	15	16	13	16	15
LWSCC #6	20	22	21	23	19	23
Average	19.0	22.3	21.0	17.5	20.5	19.7
Std. Dev.	3.29	6.06	4.55	4.43	3.94	6.02

Table 6. Summary of Predicted to Measured Values of Transfer Length

Beam	f_{se} (ksi)	Predicted l_t (in.)	Measured Transfer Length at 28 Days			
			Live End l_t (in.)	Predicted/ Measured	Dead End l_t (in.)	Predicted/ Measured
LWSCC #1	171	28.5	23	1.24	25	1.14
LWSCC #2	168	27.9	18	1.55	13	2.15
LWSCC #3	172	28.7	27	1.06	15	1.91
LWSCC #4	170	28.4	20	1.42	27	1.05
LWSCC #5	176	29.3	16	1.83	15	1.96
LWSCC #6	175	29.1	19	1.53	23	1.27
Average		28.7	20.5	1.40	19.7	1.46

Development Length

Six beams were tested to failure by applying a point load at varying lengths from the end. The first beam tested had an applied load at 45 inches from the end. The beam exceeded its nominal moment capacity and exhibited strand fracture. No slip was detected during this test. The second beam was loaded to failure at 35 inches from the end. Slip occurred approximately at the same time a large shear crack developed. The remaining four beams all failed by bond failure. Slip was observed in each case. Development length may be determined experimentally by finding the embedment length at which strand slip occurs at nominal moment capacity of the beam. Tests were conducted at progressively shorter embedment lengths until strand slipped below nominal moment capacity. All of the tests at or greater than 27.5 inches experienced failures greater than the nominal moment capacity. The test at 25 inches was the only test that experienced failure by bond failure below the nominal moment capacity. According to test results, the development length was between 25 inches and 27.5 inches (Table 7).

Table 7 Summary of Embedment Length Test Results

Beam	Embedment Length (in)	Moment at Failure (k-in)	Nominal Moment Capacity (k*in)	Failure Moment/ Nominal Moment	Failure Type
LWSCC#1	45.0	916.3	751.2	1.22	Strand Fracture
LWSCC#2	35.0	900.7	747.0	1.21	Shear Crack/Bond
LWSCC#4	30.0	854.1	751.7	1.14	Bond
LWSCC#3	27.5	830.8	755.9	1.10	Bond
LWSCC#5	25.0	731.3	755.4	0.97	Bond
LWSCC#6	27.5	856.0	760.5	1.13	Bond

The experimentally determined development length was compared to those predicted by code. The following formula is presented in ACI 318-05.[6]

$$l_d = \left(\frac{f_{se}}{3000}\right)d_b + \left(\frac{f_{ps} - f_{se}}{1000}\right)d_b \quad \text{Eqn(4.4)}$$

For the beams tested using 0.5 inch diameter strands, the calculated development length ranged from 74.5 inches to 77.0 inches. The range of experimentally determined development lengths of 25 inches to 27.5 inches is therefore significantly less than the values predicted by code equations. The codes appear to be very conservative for LWSCC. In the case of 0.5 inch strands and for these tests, the codes predicted a development length approximately 3 times that which was determined experimentally.

DISCUSSION

The measured transfer and development lengths were much less than the estimated values derived from the ACI equations. There are several avenues to explore when attempting to explain these differences. The first avenue is strand condition. Upon arrival from the manufacturer the strands were stored indoors to preserve the clean, rust free surface. It is unlikely that strand condition was the cause of the shorter than expected transfer and development lengths. Another possible option is the method of strand detensioning. In this project, the strands were gradually released instead of flame cut. Research has shown that this type of detensioning can reduce transfer lengths.[11] Another option is the concrete. The fluidity of SCC may provide for improved consolidation around the strands compared to that of conventional concrete which would improve strand bond.

CONCLUSIONS

The goal of this research program was to provide information on the behavior and performance of LWSCC. The conclusions of this research program are shown below:

- For the LWSCC mixtures used in the study, the ACI/AASHTO methods overestimated MOE for the mix used for the small scale beams by about 8%-18%. When accurate estimates of MOE are needed for LWSCC, it is recommended that the MOE be measured.
- For the LWSCC mixtures used in the study, the current ACI/AASHTO equations used in estimating transfer and development length in conventional concrete can be used for LWSCC.
    - The average measured transfer length at 28 days for the LWSCC beams was 20.5 inches. The ACI/AASHTO transfer length prediction equations overestimated transfer length by approximately 40%.
    - The development length for LWSCC beams using 0.5 inch prestressing strand was experimentally determined to be between 25 inches and 27.5 inches. The experimentally determined development length was approximately 1/3 of the values predicted by ACI code equations.
- This research program examined one LWSCC mixture and one 0.5 inch strand source. Future research will examine different LWSCC mixtures, 0.60 inch strand, and different types of lightweight aggregates.

REFERENCES

1. Holschemacher, K., and Klug, Y., "A Database for the Evaluation of Hardened Properties of SCC," *LACER*, No. 7, 2002, pp. 123-134.
2. Campion, M. J., and Jost, P., "Self-Compacting Concrete: Expanding the Possibilities of Concrete Design and Placement," *Concrete International,* V. 22, No. 4, 2000, pp. 31-34.
3. Janney, J. R., "Nature of Bond in Pre-Tensioned Prestressed Concrete," *Journal of the American Concrete Institute*, V. 25, No. 9, 1954, pp. 717-736.
4. Larson, K. H., Peterman, R. J., Esmaeily, A. "Bond Characteristics of Self-consolidating Concrete for Prestressed Bridge Girders." *PCI Journal*. Vol. 52, No. 4. July-August 2007. pp. 44-57.
5. Hegger, J., Bülte, S., Kommer, B. "Structural Behavior of Prestressed Beams Made With Self-consolidating Concrete." *PCI Journal*. Vol. 52, No. 4. July-August 2007. pp. 34-42.
6. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary (318R-02)," American Concrete Institute, Farmington Hills, Mich., 2005, 430 pp.
7. Kose, M. M., "Prediction of Transfer Length of Prestressing Strands Using Neural Networks," *ACI Structural Journal*, V. 104, No. 2, 2007, pp. 162-169.
8. Russell, B. W., and Burns, N. H., "Measured Transfer Lengths of 0.5 and 0.6 in. Strands in Pretensioned Concrete," *PCI Journal*, V. 41, No. 5, 1996, pp. 44-65.
9. American Association of State Highway and Transportation Officials, "AASHTO-LRFD Bridge Design Specifications," Third Edition, Washington, D.C. 2004.
10. Gross, S. P., Yost, J. R., and Gaynor, E. "Experimental Study of Prestress Loss and Camber in High-Strength SCC Beams." ACI 247, 2007, pp 77-92.

11. Russell, B.W. and Burns, N.H., "Measurement of Transfer Lengths on Pretensioned Concrete Elements," *Journal of Structural Engineering*, V. 123, No. 5, May, 1997, pp. 541-549.