EARLY AGE BOND STRENGTH OF EPOXY COATED REINFORCING STEEL IN SELF CONSOLIDATING CONCRETE

Marcus L. Knight, Ph.D., P.E., Middle Tennessee State University, Murfreesboro, TN
G. Scott Wilson, P.E., Palmer Engineering, Nashville, TN

ABSTRACT

Self consolidating concrete (SCC) has become increasingly popular due to savings in placement time, ease of finishing, and numerous other productivity and quality issues. SCC may be specified in a similar manner as conventional concrete when characteristics such as compressive strength are considered, and calculation of development length of reinforcing steel is accomplished in the same manner for both SCC and conventional concrete mixes.

The research project presented investigated the pullout strength of straight reinforcing bars of varying embedment depths in SCC and conventional concrete specimens of similar compressive strength. The results of the tests on the SCC and conventional mix indicated small to moderate variations in bond strength to compressive strength ratio when tested at early ages including 1 and 5 days.

Keywords: Self Consolidating Concrete, Bond Stress

INTRODUCTION

Due to economic savings and increases in productivity, self consolidating concrete (SCC) has become increasingly popular over the past two decades. SCC may be specified in a similar manner as conventional concrete when characteristics such as compressive strength are considered. However, the proportions of the mix designs used for these two different types of concrete vary in aggregate, fines, and admixture content. Regardless of these differences, current design practice following ACI 318 or AASHTO LRFD Bridge Design Specifications requires that the same development length be used for reinforcing bars in both SCC and conventional concrete mixes[1,2].

The research project presented investigated the bond stress developed with straight reinforcing bars in SCC concrete. The project consisted of constructing specimens of SCC and conventional concrete, each having similar plastic (air content and unit weight) and hardened (strength) properties. Straight reinforcing bars were cast into the specimens at varying embedment depths. Subsequent to curing, the bars were tested in tension to failure (concrete or steel). The results of the tests on the SCC and conventional mixes were compared to identify if there was a measurable, significant difference in the ultimate bond stress, and possibly development length, for the bars placed in SCC when compared to those in the conventional specimens.

SELF CONSOLIDATING CONCRETE

SCC is a highly flowable concrete mixture. Typically, no vibration is required during placement as SCC consolidates under its own weight. In contrast to conventional concrete mixes that are made to be very flowable by the addition of water or admixtures, SCC does not segregate when placed. Use of SCC as compared to conventional concretes results in increased efficiency in labor use. The product is more easily placed with less labor required to move the concrete throughout the forms, less manpower required to consolidate and finish the concrete, and its use may result in a safer work environment[3]. Increases in productivity may also be seen when considering pumping. Also, use of SCC helps to minimize voids around reinforcing steel, embedded items, and intricate formwork, while providing a finished surface that requires little or no additional work. Although SCC may be used in virtually any application, it is particularly suited for use at precast/prestressed plants where all of the above factors are of interest.

SCC has similar mechanical properties when compared to conventional concrete. Designers, engineers, and contractors may design following the same procedures with no code implications when using SCC. However, one major difference that must be considered when using SCC is the amount of pressure that is exerted on the formwork as compared to conventional mixes. Due to the increased flow of SCC, form pressures could increase requiring additional attention be paid to the design of the formwork.

Generally, SCC is produced with the same basic materials as conventional concrete mixes, with slight modifications in material proportions and admixture use. Superplasticizers and viscosity modifiers are used to increase the flow of the concrete and maintain the stability[3]. Deviations from a conventional mix design include an increased amount of fines or cement, smaller and less coarse aggregate, increased fine aggregate, and thus a higher fine to coarse aggregate ratio. These deviations help to provide a viscous mix that resists segregation and suspends aggregates in the paste fraction of the mix[3].

Many properties of SCC can be measured in the same way as conventional concrete. One major difference is the measurement of consistency. With SCC, this property is measured through the use of a spread test (typically 20 to 30 inches) that utilizes a conventional slump cone but measures the horizontal spread rather than the vertical drop. Other special tests include the U-box, L-box, and J-ring assemblies used to assess the ability of the mixture to pass through congested reinforcing steel spacing[3].

One property of interest is the early age bond strength of SCC mixtures as compared to that of conventional mixtures. This property is of particular interest in applications where forms are stripped and members are loaded at early ages as seen frequently in precast plants. A significant drop in the available bond stress may lead to increased development length requirements if members are to be moved or loaded at early ages. The study presented compares bond strength of SCC and conventional concrete at early ages.

METHODOLOGY

To indentify differences in early age bond strength, and indirectly development length when comparing conventional and SCC mixes, the following methodology was developed. Similar size specimens of each type of concrete mix were cast and straight reinforcing steel bars were embedded at varying depths ranging from 3 to 8 inches. Number 4 epoxy-coated reinforcing bars were used in all specimens. Specimens were tested after 1 and 5 days of curing to quantify the similarities or differences in the early age bond strength of the two mix types.

SPECIMENS

Two different options were considered when selecting the size of test specimen. The first option included the preparation of a large sample(s) and casting multiple reinforcing bars with spacing to provide adequate room for testing and to allow failure of each bar independently. The second consisted of the production of smaller specimens large enough to embed and test one bar. Although each of these options would be suitable for testing, the second option was chosen for several reasons. These included ease of production, ease of transportation and movement of samples during testing, and ease of disposal after testing was complete.

The two primary criteria for selecting the size of the specimens were maintaining the desired minimum clear cover surrounding the bar and providing appropriate size of specimen for support of the testing equipment. The desired minimum clear cover was chosen as 2 inches surrounding and below the reinforcing bar. The base of the testing apparatus was circular with a diameter of 6 3/8 inches. The concrete specimens were square, with dimensions of 7 inches by 7 inches. The depth of each specimen was set as the desired embedment plus 2 inches. The specimens were cast using wooden forms as detailed in Figure 1.

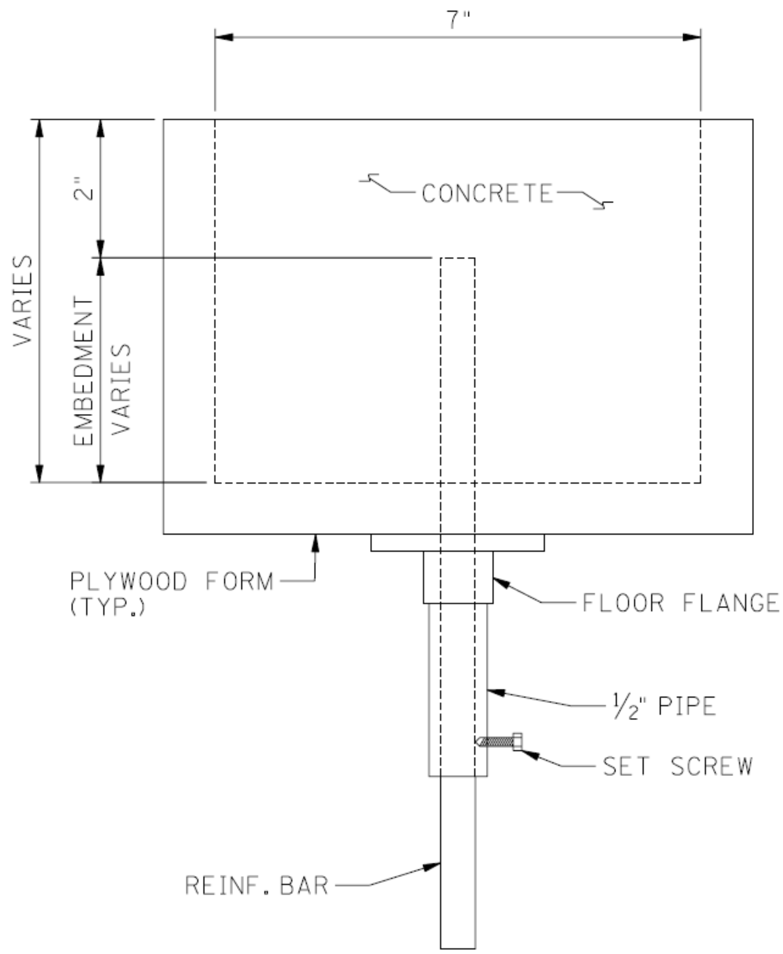

Figure 1: Schematic of Form

The forms were constructed of plywood with a 5/8 inch diameter hole in the bottom to allow the reinforcing bar to pass. A standard 1/2 inch floor flange and short section of 1/2 inch pipe were connected to the bottom of the form. The pipe included a set screw that was used to hold the reinforcing bar at the proper location to provide the desired embedment length. The forms, prior to concrete placement, are illustrated in Figure 2.

Figure 2: Wood Form Prior to Placement

This type of form required the specimens to be cast inverted, with the free end of the reinforcing bar downward. This allowed a precise setting of the embedment length for each sample, ensuring that the reinforcing bar extended perpendicular to the surface of the specimen, and provided a smooth surface for testing. Figure 3 illustrates forms prior to concrete placement.

The conventional specimens were filled by hand. Consolidation included rodding with a standard slump rod and tapping with a rubber mallet. Specimen finishing included strike off with a typical trowel. Figures 4 and 5 illustrate the compaction and finishing of the conventional specimens.

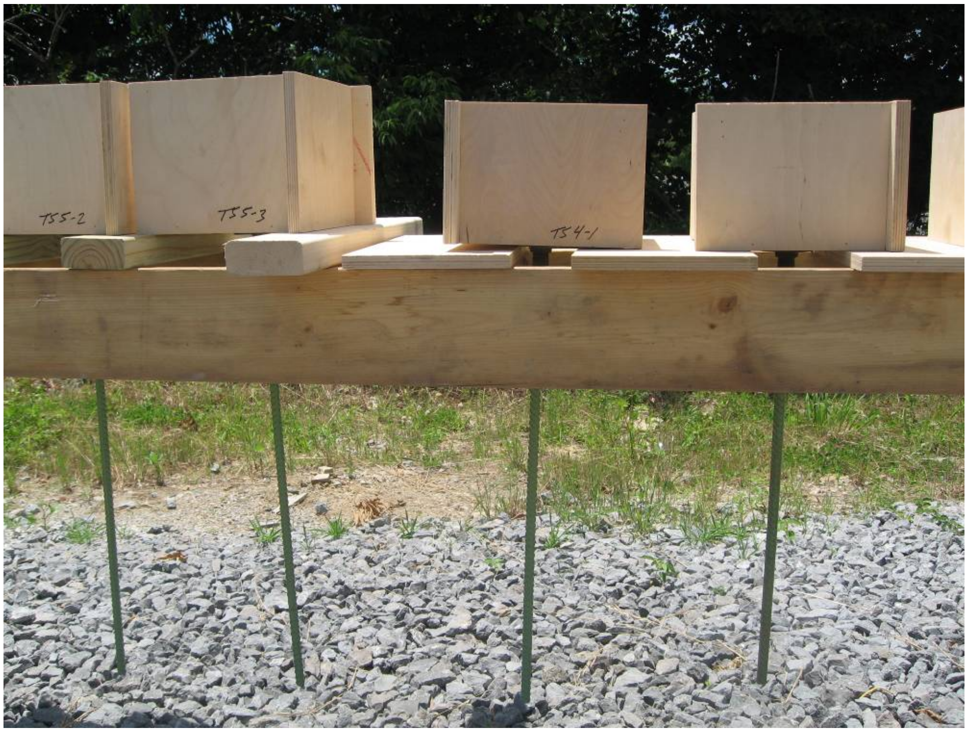

Figure 3: Forms Prior to Concrete Placement

Figure 4: Consolidation of Conventional Specimens

Figure 5: Finishing of Conventional Specimens

The SCC specimens were cast pouring the concrete from a receptacle into the forms. Consolidation included only tapping with a rubber mallet. Similar to the conventional mix, the SCC specimens were finished with a basic strike off with a standard trowel. Specimen production and the finished product are illustrated in Figures 6 and 7.

Figure 6: Casting of SCC Specimens

Figure 7: SCC Specimen Prior to Strike Off

MIX DESIGNS

A local concrete producer was consulted in the selection of a conventional and SCC mix design used for the study. Each mix was designed using the same basic materials to produce similar compressive strengths at early age and to have similar unit weights. Due to the high compressive strength typically obtained with SCC, the design process began with a typical high early strength mix already used by the producer. The mix, with a water to cement ratio of 0.36, included standard components along with a typical mid-range water reducer and accelerator. The conventional mix design characteristics are provided in Table1.

Table 1: Mix Characteristics – Conventional

Component	Quantity
Portland Cement	752 lbs
ASTM C33 Fine Aggregate	1,072 lbs
#67 Limestone Aggregate	2,020 lbs
Water	267 lbs
Mid-Range Water Reducer	75 oz
Accelerator	75 oz
w/c ratio	0.36

The SCC mix was completed through augmentation of the conventional design. The primary difference in the two mix designs was an increase in the fine/coarse aggregate ratio, reduction in coarse aggregate size, and an increase in water reducer. The characteristics of the SCC mix design are provided in Table 2. In comparison, the SCC utilized a smaller limestone chip as compared to the #67 gradation in the conventional mix. Also, the fine/coarse aggregate ratio increased from 0.53 for the conventional mix to 0.92 for the SCC mix. The cement content for each mix was the same, resulting in water to cement ratio of 0.4 for the SCC mix. Each mix was designed with no entrained air to remove one variable from the comparison between concrete types.

Table 2: Mix Characteristics – SCC

Component	Quantity
Portland Cement	752 lbs
ASTM C33 Fine Aggregate	1,375 lbs
Limestone Chips	1,500 lbs
Water	300 lbs
Mid-Range Water Reducer	60 oz
Water Reducer	70 oz
w/c ratio	0.40

TEST APPARATUS

The apparatus for testing the specimens in tension, shown in Figure 8, included a bearing plate, hydraulic cylinder and pump, load cell, and electronic instrumentation for measuring and recording load. The capacities of the load cell and hydraulic cylinder were 30 tons and 50 kips, respectively. The bearing plate consisted of two steel plates connected together. The upper plate was circular with a diameter of 6 inches, thickness of 1 inch, and contained a 1 inch diameter center hole. The bottom plate, or ring, was circular with an outside diameter of 6 3/8 inches, inside diameter of 5 3/8 inches, and was 3/8 inch thick. This ring allowed concrete in the area immediately surrounding the reinforcing bar to fail without restraint during testing. Finally, a reinforcing bar coupler and two 3/8 inch thick steel washers were used to provide support on the upper side of the apparatus during loading.

Figure 8: Testing Apparatus

REUSLTS

All specimens were cast at the plant where the concrete was batched on the same day with similar ambient and stockpile conditions. Each batch of concrete was tested prior to placement to identify the properties and modify as needed to produce the desired characteristics. The plastic properties of the conventional mix are provided in Table 3. In particular, the slump of the conventional mix was quite low at 1 ½ inches and entrapped air was 3.3%.

Table 3: Plastic Properties – Conventional

Property	Measurement
Air Content (%)	3.3
Concrete Temperature (deg F)	86
Unit Weight (lb/ft^3)	145.1
Slump (inches)	1.5

The plastic properties of the SCC mix are provided in Table 4. The spread of this mix was measured at 24 inches and entrapped air content was 2.0 %. Although slight variations were present in the plastic properties (other than consistency), no substantial impact on final test results was expected.

Table 4: Plastic Properties – SCC

Property	Measurement
Air Content (%)	2.0
Concrete Temperature (deg F)	88
Unit Weight (lb/ft^3)	143.8
Spread (inches)	24

Specimens were tested in tension until failure at ages of 1 and 5 days. Testing at each age included 12 specimens, 1 from each mix and embedment length combination. The failure loads, failure types, and calculated bond stress for each specimen are provided in Tables 5 thru 8. Bond stress was calculated as failure load over the surface area of embedded bar.

Table 5: 1 Day Results – Conventional

Embedment Length (in)	Failure Load (lbs)	Failure Type	Bond Stress at Failure (psi)
3	5,679	Bond	1,205
4	7,252	Bond	1,154
5	7,055	Bond	898
6	8,326	Bond	883
7	11,178	Bond	1,017
8	13,500	Bond	1,074

Table 6: 1 Day Results – SCC

Embedment Length (in)	Failure Load (lbs)	Failure Type	Bond Stress at Failure (psi)
3	4,313	Bond	915
4	6,252	Bond	995
5	7,630	Bond	971
6	9,187	Bond	975
7	10,126	Bond	921
8	12,907	Bond	1,027

Table 7: 5 Day Results - Tradition Slump

Embedment Length (in)	Failure Load (lbs)	Failure Type	Bond Stress at Failure (psi)
3	6,329	Bond	1,343
4	8,461	Bond	1,347
5	10,141	Bond	1,291
6	11,812	Bond	1,253
7	16,926	Bond	1,539
8	14,839	Bond	1,181

Table 8: 5 Day Results – SCC

Embedment Length (in)	Failure Load (lbs)	Failure Type	Bond Stress at Failure (psi)
3	7,095	Bond	1,506
4	6,723	Bond	1,070
5	9,187	Bond	1,170
6	10,439	Bond	1,108
7	12,196	Bond	1,109
8	14,898	Bond	1,186

The compressive strength of each mix was also determined at ages of 1 and 5 days. The results for the conventional mix were 3,020 psi and 5,030 psi at 1 and 5 days and results for the SCC mix were 2,680 psi and 5,220 psi at 1 and 5 days.

Typical failure results from the tensile tests included bar pullout and cracking of the concrete into several large portions. Also, a ring of surface concrete surrounding the reinforcing bar pulled out during testing. Inspection of reinforcing bars subsequent to failure indicated little concrete or mortar adhering to the surface of the bar. The typical failure mechanism and example of reinforcing bar condition after test completion are illustrated in Figures 9 and 10. No failures of reinforcing bars occurred due to the length of embedment and compressive strength at early ages.

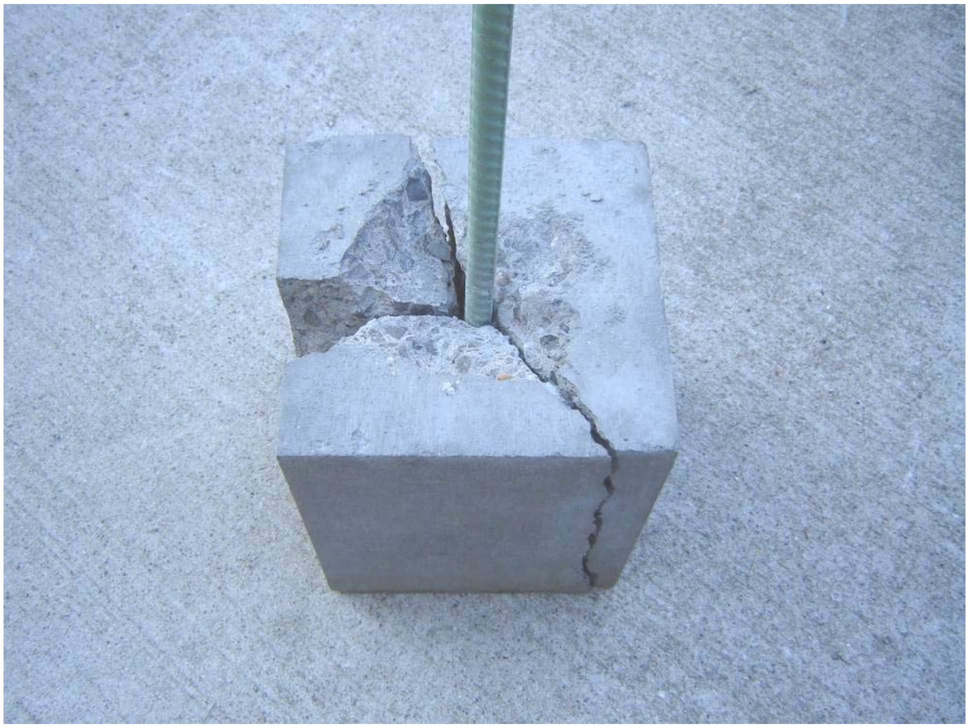

Figure 9: Typical Failure

Figure 10: Example of Reinforcing Bar after Failure

ANALYSIS

The failure loads of the specimens are plotted in Figure 11 for the 1 day tests and in Figure 12 for the 5 day tests. Also provided in these figures is the average bond stress at each embedment length. The failure load results generally followed in line with expectations with few exceptions such as the 5 day 7 inch embedment test on the conventional concrete mix. A typical increase in failure load was evident when comparing the 1 and 5 day test results.

The results were analyzed and a simple linear regression was completed on the failure load results, as shown in Figure 13. The lines generally indicate, based on the actual test results, an expected or predicted failure load. The simple linear regressions correlate well with the actual test data, with all coefficients of determination (R^2) at or above 0.89.

The results of the regression analysis were used to calculate predicted bond strengths for each mix type and age. This calculation resulted in predicted bond stresses ranging from 977 psi through 1,317 psi. A ratio of predicted bond stress to compressive strength was calculated and ranged from 0.34 to 0.26 for the conventional concrete at 1 and 5 days and from 0.36 to 0.23 for the SCC at 1 and 5 days. Results of this analysis are provided in Table 9. These results indicate that the SCC mix reached a higher relative bond stress at 1 day of age and at 5 days of age, the conventional mix reached a higher relative bond stress.

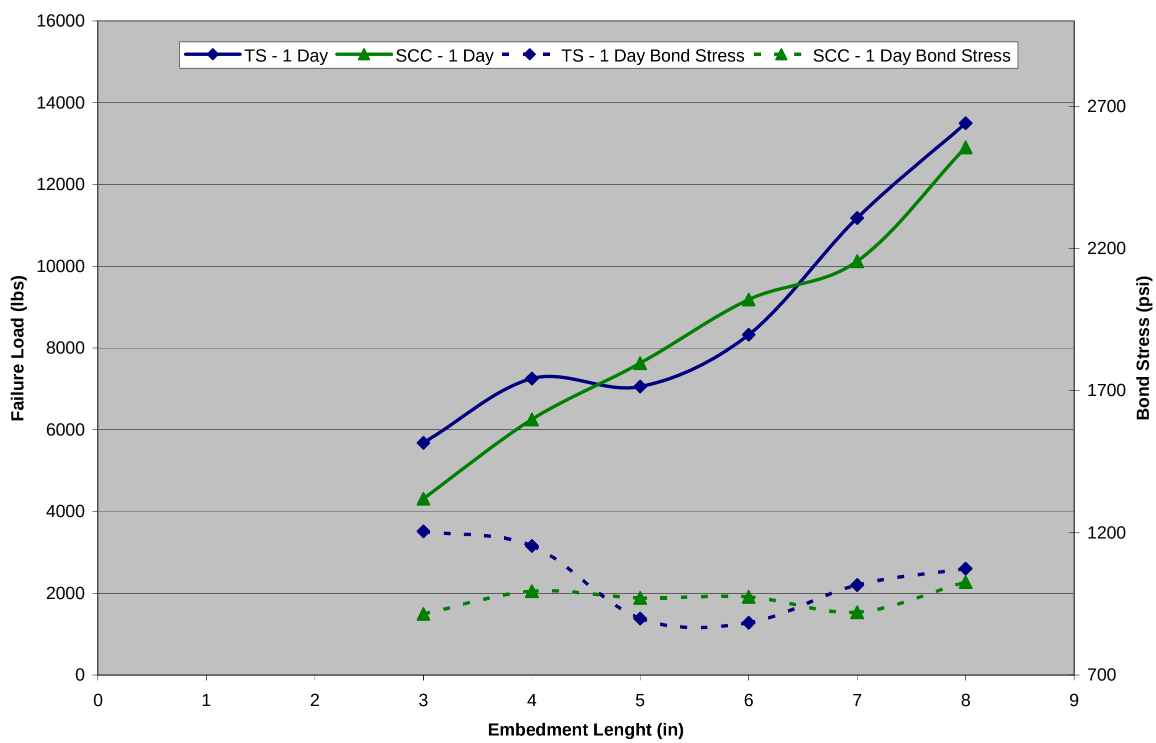

Figure 11: 1 Day Failure Loads and Bond Stresses

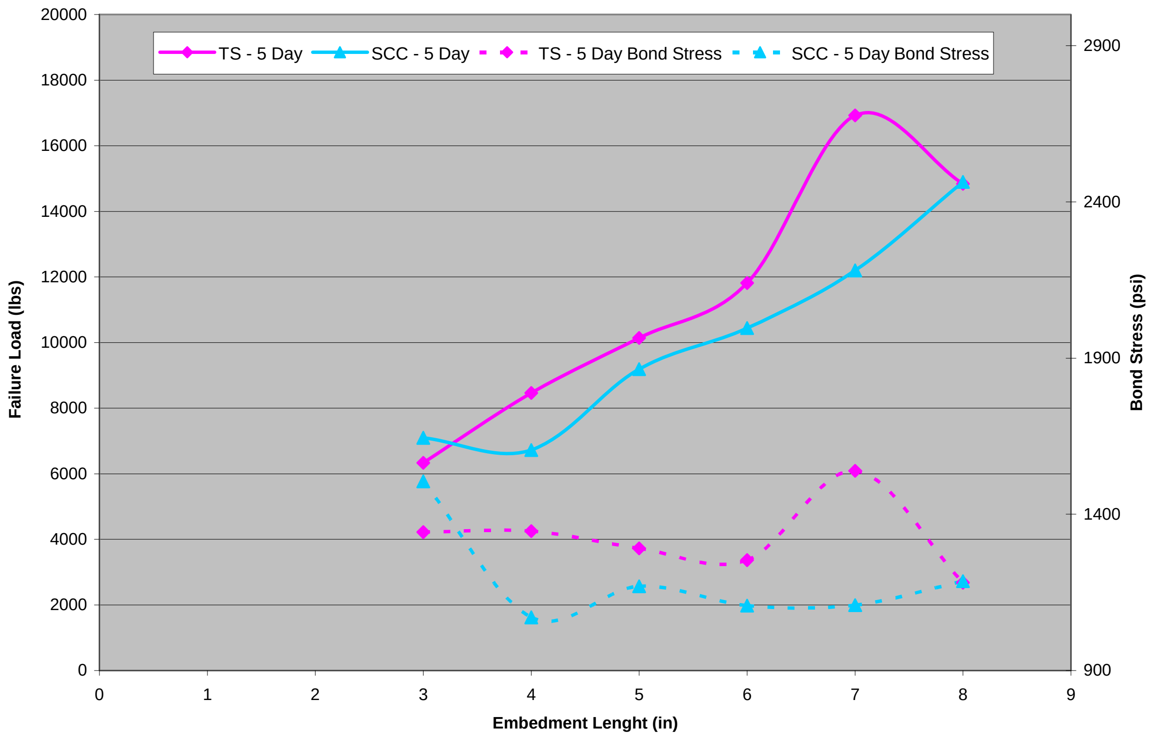

Figure 12: 5 Day Test Results

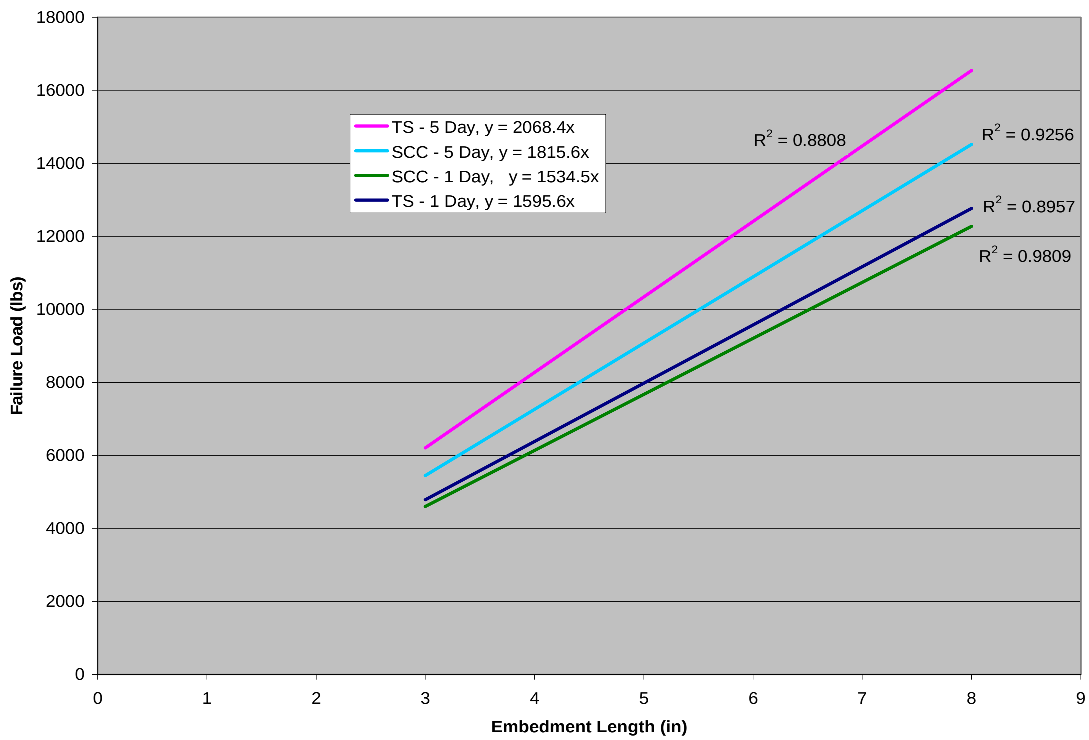

Figure 13: Regression Results

Table 9: Analysis Based on Regression Results

Specimen Material	Prediction ---	Predicted Bond Stress (psi)	Compressive Strength (psi)	Ratio ---
TS – 5 Day	y = 2068.4x	1,317	5,030	0.26
SCC – 5 Day	y = 1815.6x	1,156	5,220	0.23
TS – 1 Day	y = 1595.6x	1,016	3,020	0.34
SCC – 1 Day	y = 1534.5x	977	2,680	0.36

CONCLUSIONS

These results form the tests completed as part of this study indicate variances, ranging from 8% to 18%, in the ratio of bond stress to compressive strength for similar strength concrete specimens of similar strength and different consistencies. However, at an age of 1 day, the SCC mix appeared to have a higher relative bond stress and at 5 days, the conventional mix appeared to have a higher relative bond stress. These results do not justify any consideration of a change in development length calculation, but do support the need for further investigation into the early age bond strength characteristics of SCC. This may lead to a more thorough understanding of SCC bond stress characteristics and support implementation of code language specific to SCC and development length or provide data to support the current code language.

REFERENCES

1. ACI Committee 318, *Building Code Requirements for Structural Concrete*, ACI 318-08, and *Commentary*, ACI 318R-08, American Concrete Institute, Farmington Hills, Michigan, 2008.
2. AASHTO, *LRFD Bridge Design Specifications*, 4th edition, American Association of State Highway and Transportation Officials, Washington, D.C., 2007.
3. Kosmatka, Steven H.; Kerkhoff, Beatrix; and Panarese, William C.; *Design and Control of Concrete Mixtures*, EB001, 14th edition, Portland Cement Association, Skokie, Illinois, 2002.