EFFECTS OF CURING TIME AND CURING TEMPERATURE ON THE STANDARD TEST FOR STRAND BOND

By

C. DOUG YARHOLAR

Bachelor of Science in Civil Engineering

Oklahoma State University

Stillwater, Oklahoma

2010

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May, 2010

EFFECTS OF CURING TIME AND CURING TEMPERATURE ON THE STANDARD TEST FOR STRAND BOND

Thesis Approved:

Dr. Bruce W. Russell

Thesis Adviser

Dr. M. Tyler Ley

Dr. Robert N. Emerson

Dr. A. Gordon Emslie

Dean of the Graduate College

ACKNOWLEDGMENTS

I wish to thank my committee Chair, Dr. Bruce W. Russell, for providing me opportunities to succeed. To the other committee members, thank you for your guidance and support throughout this project.

I wish to thank Josh Albert and Jeff Rundle for their assistance and support throughout the duration of the project. Josh Albert, Doctoral candidate, and Jeff Rundle, December 2009 graduate, were essential in completion of the project.

I wish to thank my lovely wife, April, for allowing me to complete my goal of a Master of Science in Civil Engineering degree.

TABLE OF CONTENTS

Chapter Page

1. INTRODUCTION

Chapter Page

LIST OF TABLES

Table Page

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Introduction

With sponsorship from the North American Strand Producers (NASP), multiple reports and rounds of testing have been conducted on quality control test methods for strand bond quality in prestressed concrete to produce reliable and reproducible results (Russell and Paulsgrove, 1999a, Russell and Paulsgrove, 1999b, Russell and Brown, 2004, Russell, 2006). The Moustafa Test, PTI Test, friction bond test, and NASP Bond Test were amongst the test methods evaluated to determine a simple, repeatable, and robust acceptance tests for strand bond performance between prestressing strand and concrete. With exception of the friction bond test, the main method of evaluating strand prestressing strand bond utilizes untensioned strand segments casted in cementious materials. The force needed to cause relative slip between the cementious materials and the strand is used to evaluate the bond performance.

The Standard Test for Strand Bond (STSB), formerly known as the NASP Bond Test, became the clear choice. The STSB method demonstrated an ability to correlate pull-out values obtained from the test to measured transfer and development lengths and demonstrated consistent bond performance results in multiple testing sites across the country (Russell and Brown, 2004, Russell, 2006, Ramirez and Russell, 2007). To generate consistent results in evaluation of bond performance, the mortar mixture of cement, water, and sand used to cast the prestressing strand in steel cylinders must meet strength, flow, and curing environment requirements (Russell, 2006). The curing environment for the mortar requires accurate and steady climate control to develop mortar strength within the testing time frame. The proper curing conditions can be produced in research and testing laboratories which typically posses curing and/or environment chambers where temperature and humidity are regularly controlled.

Strand manufacturers and prestressing plants do not typically possess the needed climate controlled curing chambers. Many strand plants and prestressing producer plants may have covered warehouses or factories, but the environmental conditions even inside their facilities reflect somewhat the season of the year, whether hot in the summer months or cold in the winter. A poorly temperature controlled space will adversely influence the strength of the mortar, higher or lower depending on the curing temperature, and may alter pull-out values.

In addition to curing temperature, varying the amount of curing time and the w/c ratio of a mixture will adversely affect the strength of the mortar. The curing time requirement for specimens of the STSB is 24 ± 2 hrs. If the desired w/c ratio of a mixture is not achieved, the 4 hr testing frame can be challenging to accomplish while meeting mortar strength requirements. Considering another aspect of the w/c ratio of a STSB mixture, strand producers and prestressing plants could benefit from a flexible testing time frame as long as the mixtures met mortar strength requirements.

Considering previous research and the relative simplicity of the STSB method, can the curing requirements be relaxed as long as mortar strength requirements are met? NASP research conducted by Russell, Paulsgrove, and Brown determined mortar strength impacts pull-out values from the STSB method, so maintaining a mortar strength of 4,500 to 5,000 psi was imperative. The intent of this research project was to observe the effects on the STSB results from altering curing conditions while adhering to mortar strength requirements. By isolating curing time and curing temperature, the effects of these variables on pull-out values were studied to determine the validity of the results from the STSB method providing mortar strength requirements were satisfied.

1.2 Research Description

Using the STSB method, two sets of tests were conducted to address procedures concerning curing conditions. The basis of the two test programs were to conduct the STSB when mortar strength requirements were met to determine the effects curing conditions have on pull-out values. The tests addressed curing temperature and the amount of curing time separately. The modified STSB curing procedures were as follows:

(1) Alter the specified curing time of the STSB method to 18, 24, 30, 48, and 72 hours while maintaining the specified mortar strength at the time of testing by increasing or decreasing the w/c ratio. No admixtures were employed in mortar batches.

(2) Alter the specified curing temperature of the STSB method to 64°F, 73°F, and 90°F (17.8°C, 22.8°C, and 32.2°C) and test at the time when specified mortar strength was reached. The curing time was dependent on mortar strength. The mixtures used for each curing temperature variable had the same w/c ratios.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Methods of testing for bond quality have been developed over the last decade. The North American Strand Producers (NASP) funded multiple rounds of pull-out tests and research programs to seek out two objectives:

1) "Develop a simple and repeatable test that is an accurate predictor of bond performance for seven wire strand in pretensioned concrete applications," and,
2) "Identify a minimum standard value for bond performance to ensure safe and reliable structures," (Russell and Brown, 2004).

In all, the NASP sponsored four rounds or testing for strand bond. Four research reports were completed and published. A fifth round of testing, called "Round Omega" was sponsored by the American Wire Producers Association (AWPA), with the former NASP members forming a committee within AWPA. In NASP Rounds I, II, III, and IV pull-out test methods such as the Moustafa Pullout Test, PTI Test, and NASP Bond Test were evaluated and compared. The bond tests mentioned measured the pull-out strength of untensioned prestressing strand embedded in a cementitious body. The culmination of the NASP rounds of testing resulted in the Standard Test for Strand Bond.

2.2 NASP Round I (Russell and Paulsgrove, 1999a)

NASP Round I testing set out to identify a simple and repeatable test method to evaluate bond performance between prestressing strand and concrete. In this research program, three pull-out methods were reviewed for their ability to categorize bond performance and obtain results consistent with other test sites. In addition to pull-out tests, the surface residue of the prestressing strand was examined by using weigh-strip-weigh and electron optics methods. In the weigh-strip-weigh method, the strand samples were before and after soaking in acetone. The measured difference revealed the amount of residue on the strand. A scanning electron microscope (SEM) was used to identify elements within the strand residue on strand samples.

The pull-out methods examined in NASP Round I were the Moustafa Test (now called the Large Block Pull-Out Test), the PTI Test (sponsored by the Post-Tensioning Institute (PTI)), and the Friction Bond pull-out tests. The Moustafa Test utilized a large block of concrete with multiple strand segments spaced throughout. The test procedures required a concrete strength of 3.5 to 5.9 ksi at the time of pull-out testing. The PTI Test used procedures and materials similar to the current STSB method. Strand segments were casted in a grout mixture, containing cement and water, within a steel cylinder with an embedment length of 16 in. No aggregate was used in an attempt to remove variables from within the grout. The PTI Test specified a w/c ratio of 0.45 and compressive strengths between 3,500 to 4,000 psi. Due to the lack of volume stabilizing aggregates, the cement and water mixture experienced large amounts of shrinkage. The Friction Bond Test used two identical length of strand spliced together, end to end, with a mechanical crimp. The two strand lengths were 28 in., and the steel crimp was cylindrical in shape and 1 7/8 in. in length. Strand chucks were used at the ends of either strand to apply a tensile load on the spliced strands. The maximum tension was measured in a uniaxial tension test as the splice mechanism failed.

The research of these methods was conducted over multiple sites including the University of Oklahoma, Florida Wire and Cable (FWC), and Stresscon. The Moustafa and PTI Tests proved the ability to generally measure the performance of bond capacity in the strand. The methods, however, also proved to produce inconsistent in measuring pull-out values across separate testing sites. The Friction Bond Test was determined unsuitable to assess bond performance. Efforts to refine the test methods and reduce variable were suggested and examined in later rounds of testing. Regarding strand surface residue, the amount of surface residue could not be correlated to the bond performance determined by the friction bond test and the Moustafa Test. In addition, the use of a SEM was determined to be unsuitable in identifying surface residues. Although elements were detected, elements from the strand and strand residue could not be distinguished.

2.3 NASP Round II (Russell and Paulsgrove, 1999b)

The objective of NASP Round II was to continue working toward developing a relative simple, robust, and repeatable acceptance test for bond performance between prestressing strand and concrete. As in NASP Round I, multiple testing sites evaluated three pull-out bond tests. The Moustafa and PTI Test were included in NASP Round II. A new test, called "NASP Bond Test" was introduced to Round II.

The NASP Bond Test was modeled after the PTI Bond Test, but with the addition of sand into the grout matrix to help reduce volume changes occurring during the plastic stages, and during casting of the test specimens. The NASP Bond Test matched the PTI Test in everything except a mortar mixture of cement, water, and sand instead of the cement and water mixture used in the PTI Test. Both tests specified a 16 in. embedment length within the 5 in. cylinders. The NASP Bond Test would later become the STSB. For Round II testing, the PTI and NASP Bond Test required mortar strength of at least 3,500 psi before pull-out testing began. In the PTI Test, pull-out values were measured at 0.01 in. slip at the free end, whereas the NASP pull-out force was measured at 0.01 in., 0.1 in., and maximum slip intervals at the free end. The PTI and NASP Tests were performed at the University of Oklahoma and Florida Wire and Cable.

Round II used nine strand sources at each site for each of the three pull-out tests. The strand received from strand producers were assigned letters for anonymity. The strand names remained consistent through each site and series of testing. Six strand samples from a specific strand producer were used for each single test for each of the pull-out tests.

After performing the test program, the NASP demonstrated an ability to consistently rank prestressing strand from high bond performers and low bond performers. Table 1 ranks, in order of high performance to low performance, the bond performance of each strand. The results are from the first series of testing in Round II. The table illustrates the ability to consistently quantify bond performance between multiple test sites. The pull-out forces from Table 1 are plotted in Fig. 1. Figure 1 demonstrates the reproducibility between the two test sites. The high R^2 value illustrates a strong correlation between the pull-out forces measured at Florida Wire and Cable and OU. As before in Round I, although the Moustafa Test results showed the ability to relatively assess good bond performance from low bond performance, the test was not repeatable between testing sites. The NASP Bond test, however, showed promise in producing consistent results from multiple sites. The PTI Test encountered shrinkage up to 3/8 to 1/2 in. possibly contributing to variations. The NASP showed potential into developing into a repeatable bond test as well as a simple test. The mortar mixture was more workable than the water and cement mixture used in the PTI Test. In addition, less variation in pull-out forces measured at 0.1 in. slip compared to 0.01 in. or maximum slip values were discovered.

Round Two, Series One, Strand Bond Performance Rankings			
OU Site Data		**FWC Site Data**	
Strand	**Pull-Out Force (kips)**	**Strand**	**Pull-Out Force (kips)**
C	19.57	C	12.85
A	17.70	A	12.48
P	17.12	P	12.47
M	14.87	M	10.69
K	13.76	K	9.32
B	11.81	B	8.02
W	10.35	W	6.77
Z	5.68	Z	5.17
J	2.61	J	2.77

Table 1. NASP Bond Test strand bond performance rankings.

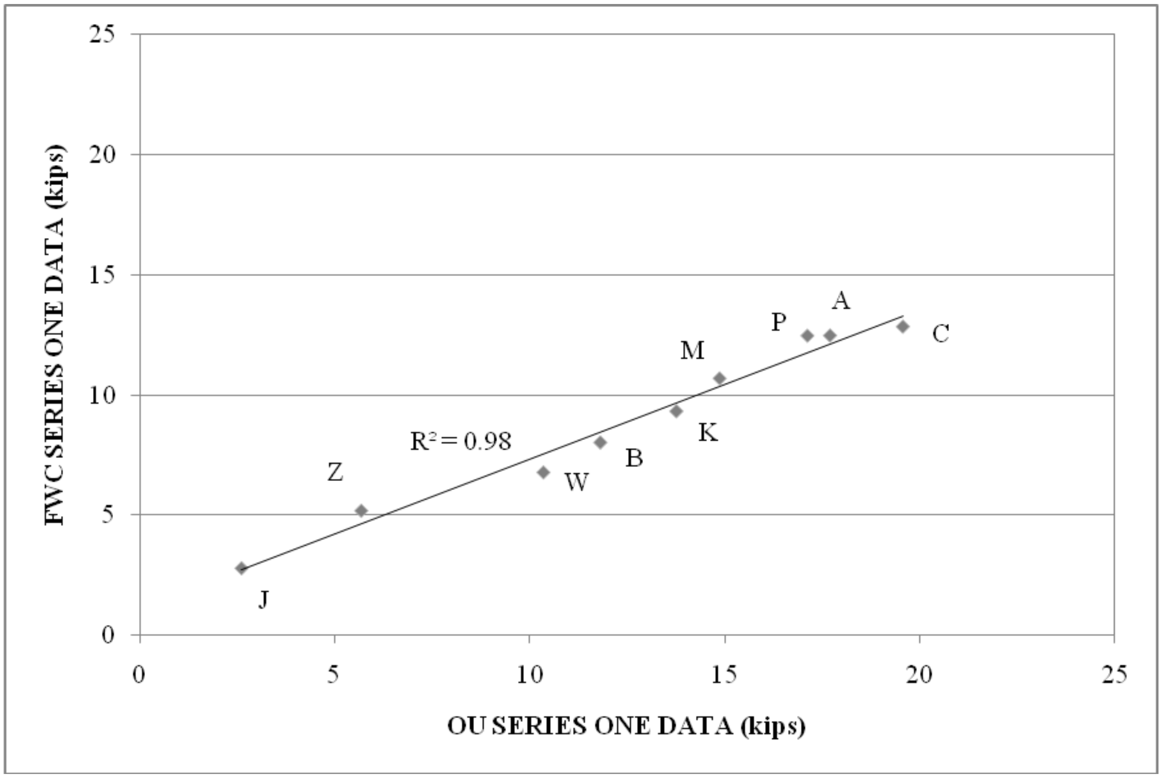


Figure 1. NASP Bond Test results – Force at 0.1 in. slip – Round Two, Series One.

2.4 NASP Round III (Russell and Brown, 2004)

NASP Round III had two primary objectives, similar to Rounds I and II. The objectives were to decrease variation in pull-out tests to develop a simple and repeatable bond performance test and to correlate pull-out values with transfer and development lengths in pretensioned beams. As in NASP Rounds I and II, the Moustafa, PTI, and NASP pull-out tests used to evaluate bond performance. The three methods used remained viable due to their simplicity and previous performances in evaluating bond quality. Alternate sites were used in an effort to confirm consistency and repeatability of test results. In addition to pull-out tests, pretensioned beams were made from strand samples used in the pull-out tests. Transfer lengths were examined, and the beams were loaded to measure development lengths. In using the same strand samples in the beams and pull-out tests, relationships and validity of the pull-out tests and beams could be observed.

In NASP Round III, the PTI and NASP Bond Tests' specifications were constricted to decrease variability in pull-out results. A ratio of 2:1 sand to cement was specified for the mortar in the NASP Bond Test. In both the PTI and NASP Bond Test, a w/c ratio of 0.45, curing temperature range of 70 to 74°F, and grout/mortar, respectively, strength range of 3,500-4,000 psi, and curing time of 18-24 hours was specified. Also, the pull-out values were measured at 0.01 in., 0.1 in., and the maximum slip at the free end for the PTI and NASP Bond Tests.

NASP Round III used ten strand sources for the three pull-out tests mentioned. There were 60 total tests using the Moustafa Pull-Out Test method, and 18 specimens were used per concrete test block. The PTI Bond Test and the NASP Bond test had a total of 60 tests with six strand per cast. The total number of tests previously mentioned was conducted both at the University of Oklahoma and Florida Wire and Cable. As for the concrete beams used to measure transfer and development lengths, 8 beams were cast and 16 total tests conducted for both the singular strand rectangular beam and the double strand rectangular beam. All of the beam tests were conducted at OU.

All three methods demonstrated an ability to rank relative bond performance. Out of the three methods, the NASP Bond Test provided the most consistent and reproducible results between the testing sites. In addition to consistency in alternate testing sites, the NASP Bond Test directly correlated to measured transfer and development lengths. As far as simplicity in the test methods, the researchers believed the PTI and NASP Bond Test were less demanding to perform, and pull-out forces measured at 0.1 in. slip provided better correlation than pull-out forces at any other slip increments. The PTI Test continued to sustain shrinkage and cracking which led to variations in pull-out values. The researchers determined the NASP Bond Test had potential to be a repeatable, simple bond performance test that would correlate to transfer and development lengths in pretensioned beams.

2.5 NASP Round IV (Russell, 2006)

The NASP Round IV test program differed from the previous three rounds in that the goal was to determine the suitability of the NASP Bond Test for adoption to assess bond performance between prestressing strand and concrete. The programs two objectives were to refine the test to enhance the variance and round robin blind testing at sites that included Oklahoma State University, Purdue University, and Arkansas University. At this point in time, NASP had adopted the test as their standard bond test based on the previous three reports. The NASP Bond Test was also known as the "Standard Method to Assess the Bond of Seven Wire Strand to Concrete."

The method became more detailed through all aspects of the testing to eliminate potential sources of variance in the pull-out forces. A w/c ratio of 0.45 was chosen to produce mortar strengths of 4,750 ± 250 psi. Other w/c ratios, such as 0.40 and 0.50, were also used to determine a specific w/c ratio. In this round of testing, the mortar flow was required to be 100 – 125. Prestressing strands were specified to be duct-taped before cutting to prevent "de-stranding" of the wires. The curing time was specified to be 24 ± 2 hrs after initial hydration, and the curing temperature was specified to be 73.4°F. Mixtures cured at w/c ratios and curing temperatures other than the specified curing conditions were batched, however, mortar strength only was tested and not pull-out forces.

Results showed that an increase in curing temperature produced an increase in mortar strengths, and to achieve mortar strengths of 4,750 ± 250 psi for a curing time of

24 ± 2 hrs, a w/c ratio of 0.45 was needed. Unit weight was measured with each batch and resulted in a weak correlation with the w/c ratio. The mortar strength was determined to play a significant role in pull-out values. Considering the alternate testing sites, the NASP Bond Test proved to be a repeatable, consistent evaluation method for bond performance of prestressing strand.

2.6 Round Omega

Round Omega, sponsored by AWPA, is currently being conducted in the Civil Engineering Lab at Oklahoma State University and lead by Dr. Russell. Publications of the on-going research have yet to be published. In Round Omega, the STSB method is being used to evaluate bond performance on strand delivered to the lab from strand producers. The prestressing strand is tested quarterly, and results are reported on bond performance.

2.7 Concrete Maturity Method (Anderson, et al., 2009)

The maturity method is a quality control technique used for estimating “in-place” concrete strength using the internal temperature of the concrete and the concrete age. Other factors such as the ambient temperature and humidity play a role. Maturity refers to the combination of temperature and cure age, and maturity is related linearly to strength gain.

Maturity curves can be developed from testing concrete strength at a known age and temperature. From these curves, strength of “in-place” concrete can be determined from calculating the maturity index. The maturity index, or maturity, is commonly expressed in °C-hours and is determined by multiplying the internal temperature of the concrete (°C) by the curing age (hrs). The most common equation used for calculating maturity in known as the Nurse-Saul Maturity Function. The Nurse –Saul function assumes linear behavior between the chemical reaction rate of hydrolysis and temperature. Nurse-Saul Maturity Function:

$$M = \sum_{0}^{t} (T - T_o) \cdot \Delta t,$$

where M = Maturity at age t

T = Average Temperature of the concrete during time interval Δt

T_o = Datum Temperature (typically -10°C)

For use in the field, temperature sensing devices are typically embedded in the concrete where they can correspond with a remote monitor that can display real-time maturity. The maturity method does have a few drawbacks, however. The mixtures used to develop the maturity curves must be the same mixtures used in placement. Also, the lack of moisture can play a critical role in the degree of hydration a mixture can achieve. ASTM outlines the procedure for utilizing the maturity method in ASTM C 1074 *Standard Practice for Estimating Concrete Strength by the Maturity Method*.

2.8 NCHRP 12-60 Report (Ramirez and Russell, 2007)

The main objective of the NCHRP 12-60 report was to recommend revisions to the AASHTO LRFD Design Specifications (2004) on the use of normal weight concrete with compressive strengths of up to 15 ksi with respect to transfer and development lengths prestressing stand. The specifications at the time of the research stated that concrete with compressive strengths exceeding 10 ksi shall be used, essentially, only when research results could prove the validity of use.

To accomplish the objectives, research was conducted to refine strand bond test protocols and evaluate correlations between the strand bond performance test and transfer and development lengths. The NASP Bond Test was used to evaluate prestressing bond performance based on the previous series of NASP reports. The NASP reports proved the NASP Bond Test was a repeatable test method when conducted across multiple testing sites. In the NCHRP report, the researchers refined the name as well, referring to the NASP Bond Test as the current form of Standard Test for Strand Bond (STSB). In addition to bond performance testing, the researchers casted pretensioned beams, both rectangular and I-beams. The rectangular beams were 17 ft. in length, and the I-beams were 24 ft. in length. Multiple beams were casted with various simple strand patterns and various concrete strengths.

STSB testing was conducted at Oklahoma State University and Purdue University. With the repeatability of the test previously proven in the NASP reports, the testing sites evaluated specific strands at both sites to determine pull-out values. The prestressing strands evaluated at the sites were to be used in the beam casting. Research was also conducted on the loading rates of the specimens in the STSB. Both displacement controlled and load controlled loading was evaluated. Displacement controlled loading was determine to provide more valuable data in evaluating bond performance and was included in the protocol of the STSB. The loading rate was to be 0.1 in/min. Other requirements from the NASP Bond Test remained the same. A modified NASP Bond Test was developed to use concrete in place of the sand-cement mortar in the standard NASP Bond Test. This was done to determine the effect of concrete strength on bond performance.

The rectangular and I-beams were pretensioned to 202.5 ksi. As mentioned previously, the strands evaluated for bond performance at OSU and PU were used in the casting of the beams. The transfer lengths were determined by measuring the slippage of the strand into the concrete at the time of release, and transfer lengths were also measured throughout the life of the beam. The development lengths were determined through loading of the beams. The beams of varying concrete strength were loaded to failure.

Three distinct failures were encountered: flexure, bond, and shear failure. Beams that failed to meet the nominal design strength had characteristics of bond failure. The prestressing strand encountered large amounts of slip at the ends.

Results from the NCHRP 12-60 report demonstrated the ability of the STSB to correlate bond performance to transfer and development lengths. Higher pull-out values from the STSB resulted in shorter transfer and development lengths. The higher performing strands also resulted in beams that encountered flexure failures as opposed to bond failures. The low bond performing strand did encounter bond failure at low strength concrete; however, in high strength concrete the low performing strand had the ability to fully develop. A threshold STSB pull-out value of 10,500 lbs was specified to meet development length assumptions. The researchers also found that higher concrete strength resulted in shorter transfer lengths. The AASHTO code equations overestimated the required development length for high strength concrete. The researchers recommended revising the code equation to include a factor of concrete strength.

CHAPTER 3

EXPERIMENTAL PROCEDURES

3.1 Test Method

A modified Standard Test for Strand Bond method was used to evaluate the strand performance. The only alterations were to the curing conditions. The Standard STSB method procedures are located in Appendix A.

The test begins with batching the mortar casting the strand within the cylinders. The appropriate w/c ratio is determined from trial batching to obtain the desired strength of the mortar at the time of testing. The w/c ratio is also adjusted for the water content of the sand compared to the absorption of the sand. Sand was used to achieve the desired amount of flow or workability and to reduce the shrinkability of the mix. After the batch weights are determined, the sand, cement, and water are weighed out to produce a volume of approximately 2.7 ft^3. Additives were not used. The mortar strength was determined by varying the w/c ratio alone. Half of the sand and water were placed in to the mixer. The mixer used was a rotating drum, shear mixer that produce up to 2.7 ft^3. The mixer was turned on and the cement was added followed by the remaining sand and water. The materials were mixed for 3 minutes, and then allowed to rest for 3 minutes and mixed again for 2 minutes. After completion of mixing, a sample is taken from the drum to the flow table. A flow test is administered to determine the flow. The cylinders are then filled halfway. The cylinders are 18 in. tall and welded to a ¼ in. square plate. The 32 in. strand is inserted into a centered hole on the plate and allowed to protrude through the bottom of the plate. The strand was fixed in the center of the cylinder at the top by a steel jig. The jig remains on the cylinder through the curing process and is removed before testing. There were 12 cylinders and strand per batch. The strand provided was from three different sources, and four strands per batch from each of the three strand producers were included in each batch. After the cylinders were filled halfway with mortar, the cylinders were mechanically vibrated until a consistent appearance was achieved. The period of time of vibration was typically 10-15 seconds. The cylinders were then filled close to the top and vibrated again. Following the vibration, a rubber mallet was used to strike the cylinders to ensure air pockets were removed. The cylinders were then completely filled, and the excess mortar was removed, and the cylinders were leveled. The specimens were transported to a curing room where they would remain until testing.

While the cylinders were filled, mortar cubes were simultaneously constructed. The mortar cubes were constructed in accordance to ASTM C 109 Standard Test Method for Compressive Strength of Hydraulic Cement Mortars. The molds used were standard 2 in. x 2 in. mortar cube molds that contained three cubes per mold. Typically four molds were used per batch producing 12 mortar cubes. In the curing temperature testing program, up to six molds were used to allow for error while trying to determine the mortar strength when the curing time was unknown. After the molds were completed, the molds were placed on the wooden frame that supported the cylinders. The molds were stored with the cylinders in the curing room.

The curing room at OSU is temperature and humidity controlled. The temperature remained at 73 ± 3°F while the relative humidity remained > 90%. The dimensions of the curing lab are 8 ft. x 8 ft. x 8 ft. During a standard test, the specimens are allowed to cure from the time the cylinders are filled until the time of testing which is 24 ± 2 hrs from the time the cement mixes with the water. The mixing procedures closely follow ASTM C 192. All the specimens from the curing time testing program were stored in this curing room. The curing time varied from 18, 24, 30, 48, to 72 hours. The test preparations were conducted inside of the curing room. Test preparations included grinding the mortar cubes until level while the cubes remained in the mold, removing the cubes from the molds, measuring the cubes with calipers to calculate the actual surface area, removing the jigs from the top of the cylinders, and brushing excess mortar from the cylinders and strand to ensure accurate readings from the testing equipment. Specimens from the curing temperature testing program were stored in a separate curing chamber where extreme temperatures could be obtained.

After the preparation of the specimens, compression strength of three of the twelve mortar cubes were determined at approximately 22 hours from the time of the mixing. If the mortar cubes meet the strength specifications of 4,750 ± 250 psi, the testing can proceed. If not, three cubes are tested at a later time depending on the previously determined strengths. In the case of the curing temperature program, six mortar cube molds were used producing 18 mortar cubes. Compressive strength of the mortar cubes was determined until the cubes met strength specifications.

After satisfying the minimum compressive strength requirements, the specimens are tested. Specimens are placed into the apparatus and recording equipment is attached. The cylinder rests on a platform and the strand fits through a slot in the platform and protrudes through the bottom. A bar that spans the diameter of the cylinder is placed on top of the strand. One end of the bar is free while the other end is hinged and connected to a magnet that is attached to the cylinder. The bar is leveled and a LVDT is attached by magnet just below the free end of the bar. The LVDT records the displacement of the strand relative to the cylinder. After attaching the equipment, the test begins. The actuator begins loading the platform that the cylinder rests on upward at a loading rate of 0.1 in/min. The strand is anchored by a chuck below the platform. The displacement is displayed on a monitor that displays strain, displacement (in), load (lbs), and loading rate (in/min). Using similar triangles, the displacement, between strand and cylinder, measured by the LVDT is twice of the actual displacement, because the strand is centered along the leveled bar while the bar is hinged on one end, and the LVDT is equally spaced on the other end. The specimen is loaded and the load (lbs) is recorded at displacements of 0.01 in. and 0.1 in. The load value (lbs) reported at 0.1 in. “slip” is used as the “pull-out” value and is used to compare all other strand pull-out values. After the displacement reaches 0.1 in., the test is allowed to run for another 60 seconds to collect all necessary data. Software that runs the testing program continuously records the load, loading rate, strain, and displacement. The data is saved to file for possible later access. Upon completion of the test, the previously tested specimen is removed and replaced by the next. The test is conducted for all 12 cylinders. The compression strength of mortar cubes is determined twice more following the testing of 6 cylinders and 12 cylinders. Three mortar cubes are used in each instance. The compression strength of all the mortar cubes tested during the duration of the STSB are averaged and used for reporting the compression strength of the mortar. The average mortar strength must be within the range of 4,500 to 5,000 psi for the test to be valid. The specimens and the fractured mortar cubes are discarded, and the data is recorded.

3.2 Test Materials

3.2.1 Mortar

The STSB method requires using a mortar mix consisting of cement, sand, and water. In the preliminary NASP tests, a mixture of cement and water was used. The sand was added to control shrinkage and workability. For the curing time testing program, additional sand was used to meet flow requirements. Additives were not used in the production of the mixes.

3.2.1.1 Fresh Properties

The fresh properties determined in the mortar were flow and unit weight (lbs/ft^3). The flow was determined by taking a sample from the freshly mixed mortar and placing the sample in a cone mold on the flow table. The flow test was completed in accordance with ASTM C 230. The cone filled mortar was allowed to rest for one minute, and the cone was removed. The table was consistently rotated and allowed rise and free fall in one revolution for 15 seconds. Four evenly spaced measurements were taken across the diameter of the sample. The addition of the four measurements results in the reported flow value. A value of 100 – 125 was desired. In the STSB, if the flow value is less than 100, the mix is allowed for further mixing and the addition of water. If the flow does not meet the specifications after further mixing, the mortar is discarded. In these set of tests however, if the flow did not meet the specifications, the mortar was accepted without the addition of water because of the possibility of affecting the mortar strength at the time of mortar strength testing.

The unit weight of the mortar was found by using a unit weight bucket with a volume of 0.1 ft^3. The pre-weighed bucket was filled in three equal lifts and rodded 25 times in accordance to ASTM C 138 Standard test method for Density, Yield, and Air Content of Concrete. After striking off the excess mortar, the bucket was weighed and the unit weight was reported in lbs/ft^3. ASTM C 138 was used more as a guideline given the testing procedure is for concrete and mortar was used in this testing program. In addition, only one reading per batch was measured, and the 0.1 ft^3 volume bucket used during the process of determining unit weight was insufficient according to ASTM C 138. The stated allowable precision between unit weight measurements in a single batch average around 2.0 lb/ft^3, depending on one or multiple recorders.

3.2.1.2 Hardened Properties

The compressive strength of the mortar cube was the only hardened property of the mortar. Mortar cubes were produced following ASTM C 109 procedure. Typically four molds containing three cubes each were used per batch. For the curing temperature testing program, up to six mortar cube molds were used. Because the amount of curing time needed for the mortar cubes to reach the required strength was unknown, additional mortar cubes were needed to ensure enough cubes would be available. Before the mortar cubes were tested, the edges of the cubes were grinded and numbered. Mortar cubes with larger or numerous air pockets were tested only if needed. The dimensions of the faces of the mortar cubes that were to be in contact with the compression machine were measured. The cubes were measured with calipers and dimensions were reported to the nearest thousandth to ensure an accurate surface area and thus compression strength. Three cubes were tested before the STSB began. If the compressive strength was within the 4,500 to 5,000 psi range, the STSB would start. If the mortar cubes were less than the specified compressive strength, three mortar cubes would be tested at a later time, depending on the difference in the specified strength and the actual strength. If the mortar cubes were greater than the specified strength, the STSB would begin; however, the pull-out values would irrelevant. In the case of the curing temperature program, sets of three mortar cubes were tested until the mortar cubes reached the specified compressive strength. After pull-out values from six cylinders were determined, three more mortar cubes were evaluated for compressive strength. Following the completion of the STSB, the final three mortar cubes were tested for compressive strength, and the average of all nine mortar cubes were reported as the compressive strength of the mortar.

3.2.2 Cement

Type III high early strength cement produced by Buzzi UNICEM Lonestar INCOR was obtained from Dolese Co. and used in the mortar batches. The cement source remained the same throughout the length of the project.

3.2.3 Sand

The sand used in the mortar was provided by Dolese Co. (Dover, OK). ASTM procedures were used to determine absorption, unit weight, and gradation. ASTM C 702 Practice for Reducing Samples of Aggregate to Testing Size was used in co-ordinance with ASTM C 128 Test method for Density, Relative Density, and Absorption of Fine Aggregate to sample the sand and determine the densities and absorption of the sand. The absorption percentage was determined from the densities of the sand. The SSD specific gravity and absorption percentage can be seen in Table 2. A sieve analysis was performed to determine gradation according to ASTM C 136 Standard Test Method for

Sieve Analysis of Fine and Coarse Aggregates. The results of the sieve analysis and the fineness modulus of the sand are reported in Table 3. The sand was tested before batching started and the source remained the same throughout testing.

Samples of sand were obtained from each mixing bucket of sand used in a batch. The samples were weighed and placed in an oven, and the water was allowed to evaporate. The oven-dried samples were weighed. The difference in the weights was reported as the moisture content of the sand. The batch weights were adjusted according to the moisture content of the sand.

Sample	Specific Gravity, SSD	Absorption %
1	2.622	0.422
2	2.618	0.438
3	2.617	0.420
Avg.	**2.619**	**0.427**

Table 2. Properties of sand used for batching.

	Sample 1		Sample 2	
Sieve #	**% Passing**	**Cumulative % Retained**	**% Passing**	**Cumulative % Retained**
#4	99.3	0.75	99.2	0.76
#8	94.7	5.33	94.8	5.22
#16	80.4	19.6	80.5	19.5
#30	51.4	48.6	51.8	48.2
#50	18.4	81.6	18.7	81.3
#100	2.26	97.8	2.34	97.7
Pan	-	100.0	-	100.0
	F.M.	**2.54**	**F.M.**	**2.53**

Table 3. Sieve analysis of sand used for batching.

3.2.4 Prestresssing Strand

The prestressing strand used was a seven wire, 0.5 in. diameter, low relaxation strand. The strand had a modulus of elasticity of 28,000 psi and yield strength of 270 ksi. The strand had a cross-sectional area of 0.153 in^2.

The sampling of the prestressing strand consisted of pulling the strand from the coil, measuring the samples, and taping the ends of the samples with duct tape, and cutting the samples. Each strand sample was 32 in. The samples were spaced at 4 in. along the strand. Duct tape was used to tape the ends of the samples to keep the seven wires from unwinding. A steel cutting blade was used to cut the samples. The ends of the samples were then grinded. The bottom end of the strand was grinded so that the strand chuck could easily be fit over the strand. The top of the strand was grinded in the shape of a cone and the king, or center, wire was exposed. The king wire was exposed for a reference from which to measure the displacement.

Bond breakers were attached to the strand. The 2 in. cylindrical foam bond breakers were attached 8 in. from the bottom. The bond breakers rested on the inside of the bottom plate in the cylinders. The bond breakers reduced the stresses that accumulated at that specific point in the cylinder.

Three control strand were used in the tests. The sources of the strand were undisclosed and named Control A, J, and C. The source and manufacturing process of the control strands were not important to the results of this test. The comparison of the pull-out values from the STSB and the altered curing methods were more relevant than the strand source. The control strands have multiple pull-out values to reference to compare to results from testing.

3.2.5 Cylinders and Plate

The 5 in. diameter, 16 gauge steel cylinders used in batching samples were shipped in bundles as 20’ sections from Central Steel in Chicago, IL. The cylinders were cut down to 18 in. ¼ in. Plate was bought from Stillwater Steel in Stillwater, OK, and was 12 ft. in length and 6 in. wide. The plate was cut into 6 in. by 6 in. sections and a 9/16 in. hole was drilled in the center to allow the strand to pass through the plate. The cylinder was welded completely around the circumference of the cylinder to the plate.

3.3 Trial Batching

To determine the appropriate w/c ratio to be used in the actual test program, trial batching was conducted. Additives were not used. The mortar consisted of only cement, sand, and water. Each curing time dependent variable had a different w/c ratio. The idea of the trial batching was to determine w/c ratios for each mix that would produce the same mortar compressive strengths when cured for different amounts of time. Trial batches with w/c ratios of 0.420, 0.470, 0.520, and 0.575 were mixed for each curing time dependent variable (18, 24, 30, 48, and 72 hrs). Three mortar cubes were made for each variable at each w/c ratio. A trial batching schedule was made to accommodate the use of only ten mortar cube molds. The molds produced three mortar cubes. The cubes and molds were stored in the lab's curing room and allowed to cure for each of the curing time dependent variables. The cubes were then prepared and the compressive strength of the mortar cubes was determined.

Each variable (18, 24, 30, 48, and 72 hrs.) had a set of three mortar compressive strengths at w/c ratios of 0.420, 0.470, 0.520, and 0.575. The mortar strength was plotted against the w/c ratios for each curing time. A linear regression was fit to the data, and by using linear interpolation, the w/c ratio that produced a mortar compressive strength of 4,750 psi was selected for each curing time.

The compressive strength results from trial batching are presented in Table 4. Standard 2 in. x 2 in. mortar cube molds were used for casting. The procedure for casting the mortar cubes was ASTM C 109. As reported in Table 4, the 0.470 w/c ratio mix cured for 30 hours, a cube was disregarded because the compressive strength was more than 8.7% from the average of the other cubes. This was done in compliance with ASTM C 109 Section 13. Figure 2 shows a plot of the compressive strength results for each curing time variable along with R^2 value of the linear regression. From the regression analyses, a w/c ratio was selected for each curing time variable to yield mortar cube compressive strengths of 4,750 ± 250 psi for the actual batches. The resulting w/c ratios from trail batching are shown in Table 5. In addition, Fig. 3 shows a plot of the compressive strengths against the curing time for each w/c ratio along with the R^2 values for a power regression. Further discussion on this plot as well as error and standard deviation of error from predicted compressive strengths can be found in Chapter 5.

After a review of results and data, a mistake was found in moisture calculations of sand. The mistake began with the first trial batch and continued through the last testing program batch. The mistake was corrected resulting in an under-estimation of water and a higher actual w/c ratio in each mixture. The trends and correlations of the results were unaffected.

The w/c ratios determined in Table 5 had to be altered in some mixes to meet compressive strengths. The sand used in the mixes was stored outdoors, open to the weather. In addition to the moisture calculation mistake, during trial-batching, the sand had low moisture content from exposure to sunlight and lack of rain. In between the time of trial-batching and modified STSB testing, rain increased the moisture content of the sand dramatically. Moisture corrections were used in every mix, trial-batching and modified STSB. However, the extreme variations between low and high moisture contents might have contributed to unexpected mortar strengths. The actual w/c ratios used in the modified STSB testing are displayed in Tables 6 and 7 in the next chapter.

Average Compressive Strengths of Mortar Cubes (psi)					
W/C Ratio	**Cure Time**				
	18-hr	**24-hr**	**30-hr**	**48-hr**	**72-hr**
0.420	5273	5725	6272	7300	8113
0.420	5308	5447	6493	6965	7401
0.420	5304	5844	5921	7652	7926
0.470	4154	5096	5536	6335	6550
0.470	4356	4958	5620	6329	7143
0.470	4255	4953	-	6043	6957
0.520	3433	3794	4559	5253	5712
0.520	3367	3953	4465	4976	5641
0.520	3368	3948	4480	5356	5734
0.575	2657	3563	4074	4416	4761
0.575	2622	3259	3946	4393	4948
0.575	2666	3461	3582	4408	4877

Table 4. Compressive strength results from trial batching.

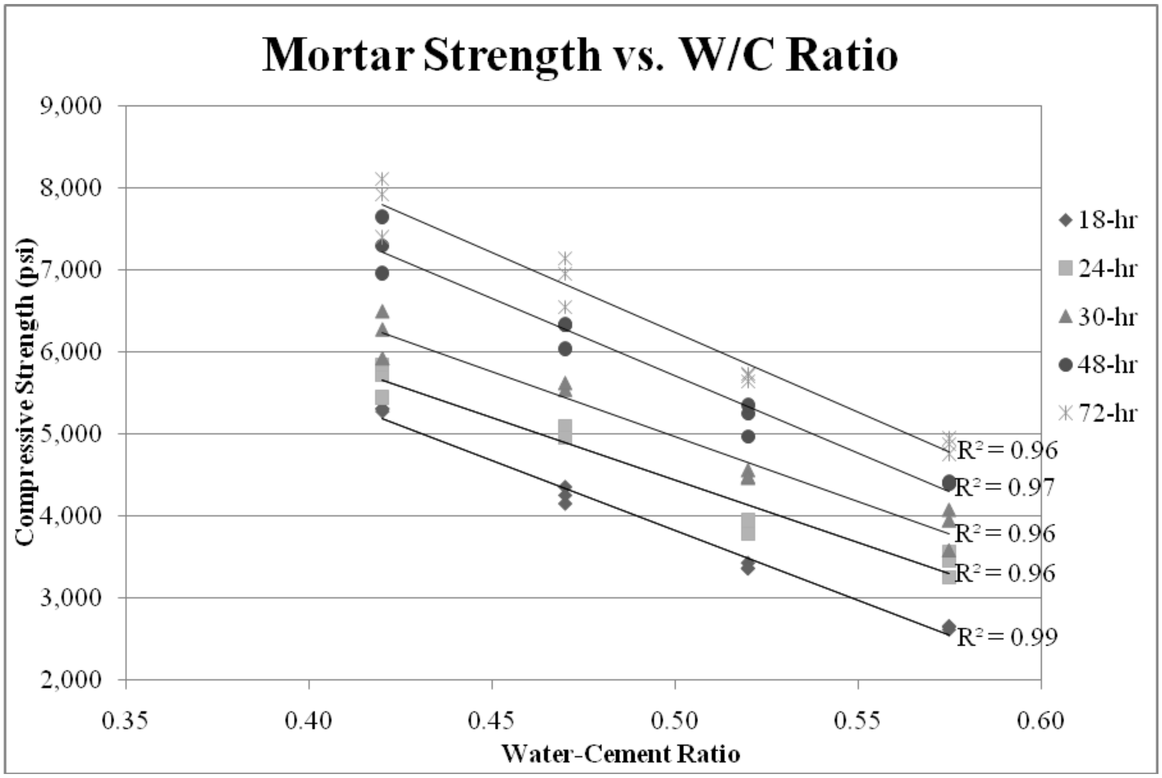


Figure 2. Compressive strength of mortar cubes from trial batching.

Trial Batching Results		
Mix	**W/C Ratio**	**R^2 Value**
18-hr	0.466	0.99
24-hr	0.480	0.96
30-hr	0.514	0.96
48-hr	0.551	0.97
72-hr	0.577	0.96

Table 5. W/C ratio results from trial batching.

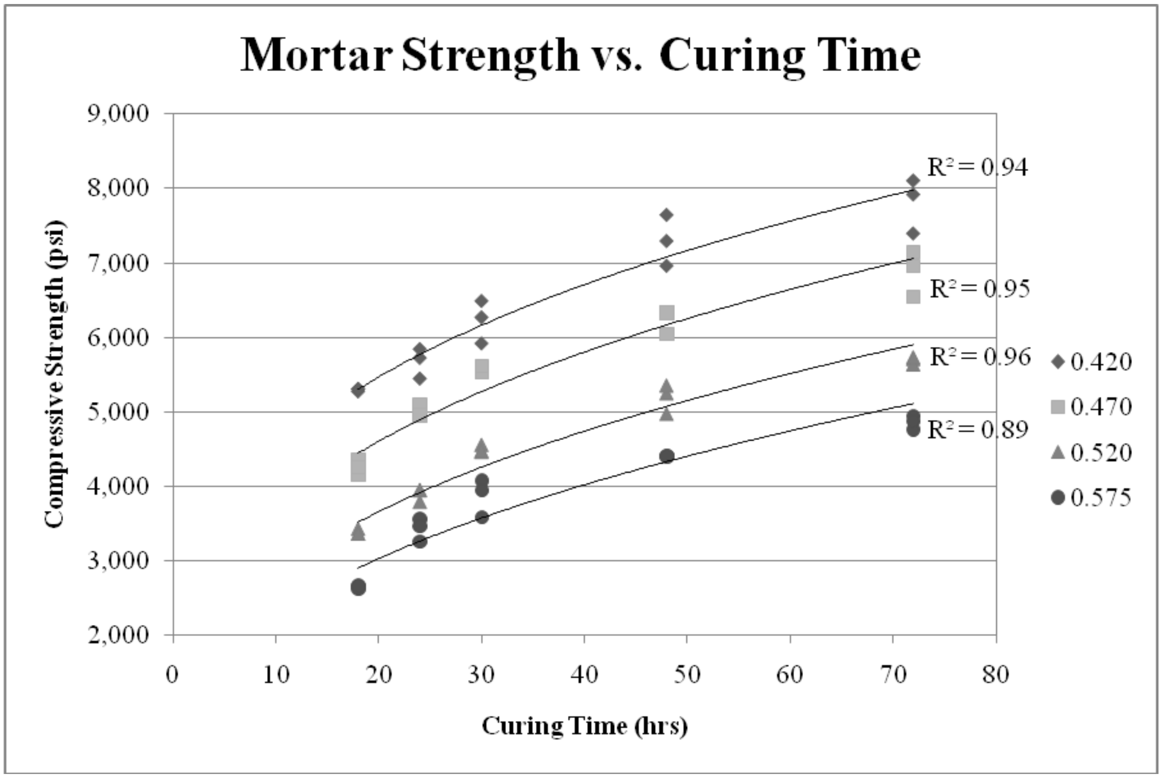


Figure 3. Compressive strength of mortar cubes from trial batching vs. curing time.

3.4 Environmental Chamber

An environmental chamber was constructed to facilitate constant temperatures of 64°F and 90°F. The chamber was constructed out of 2 in. x 4 in. wood studs and ¼ in. – ¾ in. plywood sheeting. The interior walls and ceiling were insulated with R-13 fiberglass insulation. All seams on the interior were caulked, and moisture barrier plastic sheeting was attached across the interior walls and ceiling. Weather stripping materials were used along the edges of the doors in the front of the curing room. The floor space of the curing room was 6' wide x 12' long x 8' tall providing a volume of 576 ft^3. A combination heating/air conditioning unit was purchased and installed along the side of the chamber. The cooling unit was rated at 18,000 BTU and the heating unit was rated at 12,000 BTU. The minimum recommended for BTU for the curing floor space was 5,000 BTU. Two humidifiers rated for 1,250 ft^2 of coverage were used to regulate the relative humidity in the curing room. As the temperature increased the relative humidity decreased. Multiple five gallon buckets filled with water were stored in the curing room to add surface area of water and increase the relative humidity. An electrical space heater was used in combination with the heating unit to reach and maintain a constant temperature of 90°F. The temperature and relative humidity was monitored throughout the curing process with a wireless temperature and relative humidity sensor.

CHAPTER 4

PRESENTATION OF RESULTS

4.1 Introduction

The results from the test program, curing time and temperature, and trial batching are presented in this section. All mixtures, regardless of average acceptable compressive strength of the mortar cubes, are shown in Tables 6 and 7. If compressive strength requirements were not met, pull-out values were found by the STSB and additional mixtures that met required compressive strengths were batched. The plots shown in this chapter include pull-out values and mix properties of mixtures that met the compressive strength requirements. The results are presented in two sections: (4.2) Samples cured for periods of 18, 24, 30, 48, and 72 hour, (4.3) Samples cured in temperatures of 64, 73, and 90°F.

4.2 Curing Time Data

The results from the curing time test program using a modified STSB are shown in Table 6. The table shows the pull-out values for each strand and mix properties for each mix. The pull-out values were determined at 0.1” slip using the STSB method. The mixtures were named by the amount of time the samples were cured for at 73°F, and the number of the mix is labeled in the parenthesis. For example, the first mix cured for 18 hours is labeled 18-hr (1). In some cases (18, 30, and 72 hr), the compressive strength of the mortar cubes did not meet the required compressive strength at the specified curing time, resulting in additional mixtures. The originally miscalculated moisture content samples could have led to mixtures not meeting specified strength.

The w/c ratios found from trial-batching were intended to be used in the modified STSB mixtures. As presented in Table 6, the w/c ratios had to be altered. Mix 24-hr (1) was the first to be batched. The compressive strength of the mortar met the required mortar strength. However, the next mix, 18-hr (1) failed to meet the required compressive strength. For mix 18-hr (2), the w/c ratio was increased to accommodate for the high compressive strengths. The increase of the w/c ratio was applied to each additional mix to meet compressive strength requirements. The 48-hr (1) mix produced low mortar compressive strengths. The w/c ratio was decreased to produce higher compressive strengths in the next mix. The results from trial-batching were used as a base for designing the mixtures. Explanations of moisture corrections and conditions of the sand used in mixing can be found in section 3.3.

Additionally, the pull-out value for control strand C-4 in mix 18-hr (2) was unable to be determined. Multiple wires began to separate from the strand and king wire. This error is typical when the tension clamps that grip the strand from below undergo substantial wear. The tension clamps were replaced and the test resumed.

Figure 4 displays a plot of the curing times against the pull-out values for each control strand. A power regression was used to fit the data. The R^2 values are also displayed to show the strength of the correlation.

Pullout Load Values at 0.1" Slip (lbs)								
	Mix (Variable Cure Time @ 73°F)							
Mix Name	**18-hr (1)**	**18-hr (2)**	**24-hr (1)**	**30-hr (1)**	**48-hr (1)**	**48-hr (2)**	**72-hr (1)**	**72-hr (2)**
Mix Cure Time (hr)	**18**	**18**	**24**	**30**	**48**	**48**	**72**	**72**
Mix Temperature (°F)	**73**	**73**	**73**	**73**	**73**	**73**	**73**	**73**
Water-Cement Ratio	**0.430**	**0.447**	**0.476**	**0.515**	**0.568**	**0.556**	**0.563**	**0.576**
Unit Weight (lb/ft^3)	**136.3**	**139.5**	**135.1**	**138.8**	**137.7**	**138.0**	**137.9**	**137.6**
Avg. Mortar Str. @ Test	**5,227 psi**	**4,787 psi**	**4,905 psi**	**4,636 psi**	**4,318 psi**	**4,637 psi**	**5,188 psi**	**4,767 psi**
Strand 'A'								
A-1	17,900	17,000	15,900	10,800	9,600	11,200	10,100	10,200
A-2	19,600	17,200	14,700	11,500	8,200	11,200	10,200	11,900
A-3	17,300	19,700	15,700	12,400	8,900	11,700	11,500	12,700
A-4	18,800	19,200	14,700	13,200	8,900	11,400	11,100	13,800
Avg.	**18,400**	**18,275**	**15,250**	**11,975**	**8,900**	**11,375**	**10,725**	**12,150**
Std. Dev.	**1,010**	**1,374**	**640**	**1,047**	**572**	**236**	**685**	**1,515**
Strand 'C'								
C-1	9,700	8,300	10,600	8,700	6,600	6,600	8,000	9,000
C-2	8,300	9,600	8,700	8,500	5,000	6,500	8,200	6,800
C-3	8,700	-	8,700	8,400	7,200	6,100	7,600	8,800
C-4	7,400	9,300	9,100	7,000	6,400	5,900	8,000	7,900
Avg.	**8,525**	**9,067**	**9,275**	**8,150**	**6,300**	**6,275**	**7,950**	**8,125**
Std. Dev.	**954**	**681**	**903**	**777**	**931**	**330**	**252**	**1,005**
Strand 'J'								
J-1	26,000	28,200	19,100	15,200	12,000	17,000	14,700	14,500
J-2	27,900	27,800	21,400	16,600	12,600	15,000	15,400	14,500
J-3	25,400	29,500	16,500	15,200	13,900	15,700	16,200	15,400
J-4	26,400	28,900	17,000	15,800	13,300	16,800	13,800	14,300
Avg.	**26,425**	**28,600**	**18,500**	**15,700**	**12,950**	**16,125**	**15,025**	**14,675**
Std. Dev.	**1,066**	**753**	**2,238**	**663**	**827**	**943**	**1,021**	**492**

Table 6. Pull-Out values from modified STSB and mix properties for each curing time.

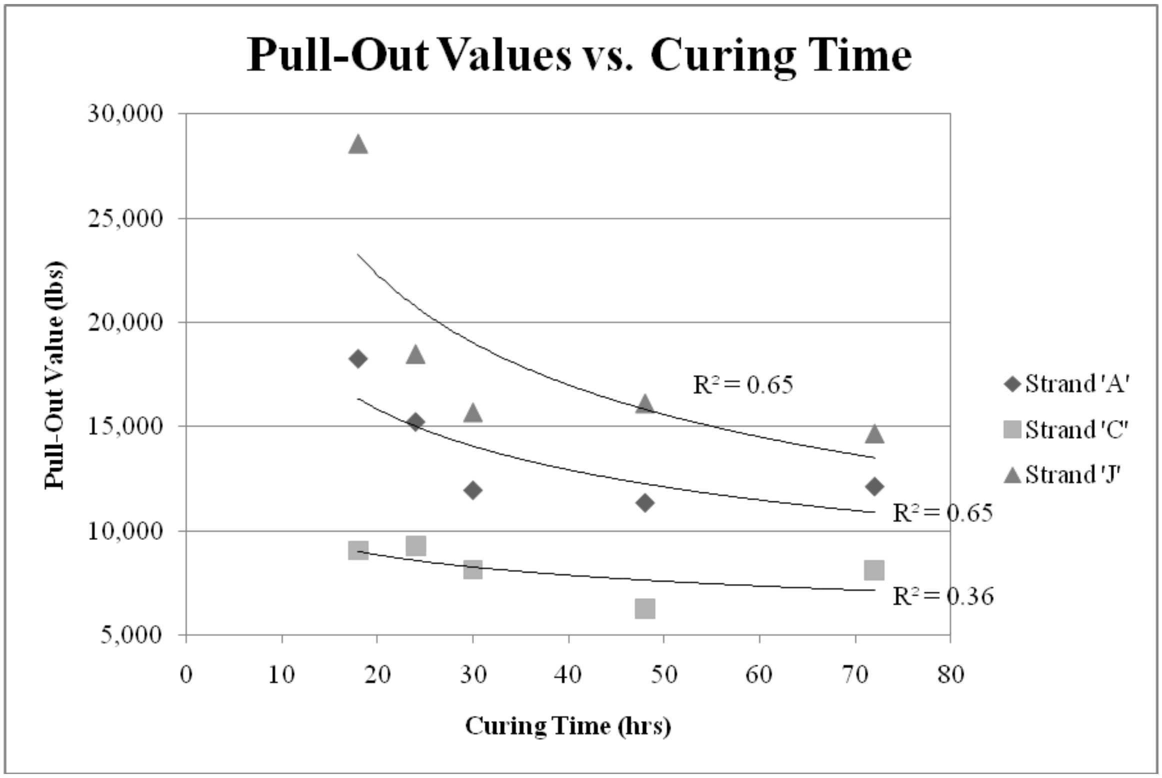


Figure 4. Pull-Out values from modified STSB plotted against curing time.

4.3 Curing Temperature Data

The results from the curing temperature test program using a modified STSB are shown in Table 7. The table shows the pull-out values for each strand and mix properties for each mix. The pull-out values were determined at 0.1 in. slip using the STSB method. The mixtures were labeled by the temperature at which the samples were cured, and the number of the mix is labeled in the parenthesis. For example, the first mix cured at 64°F is labeled 64°F (1).

In the curing temperature test program, the w/c ratio was held the same for mixtures cured at temperatures of 64, 73, and 90°F. The mixtures were tested when the mortar reached a compressive strength of 4,750 ± 250 psi. With three different curing temperatures, the mixtures were cured for different amounts of time depending on the mortar strength. The time needed for curing is also displayed in Table 7.

The 73°F (1) mix and results were taken from the curing time test program and used to compare against mixtures with the same w/c ratios and curing temperatures of 64°F and 90°F. This was done because the mix met the requirements of the curing temperature program for a mix cured at 73°F. As reported in Table 7, mixtures 64°F (1), 64°F (2), 90°F (1), and 90°F (2) had slightly higher w/c ratios. This was done with regard to the explanation in the previous section and section 3.3. Mix 73°F (1) was the first mix of all testing programs, and the curing temperature program mixtures occurred approximately one to two months later. The w/c ratios of mixtures 64°F (1), 64°F (2), 90°F (1), and 90°F (2) were intended to produce equivalent compressive strengths to mix 73°F (1). Mix 90°F (1) cured faster than expected and had compressive strengths that were higher than the required compressive strengths. The mix was reproduced and met the required compressive strength. Explanations of moisture corrections and conditions of the sand used in mixing can be found in section 3.3.

Mix 64°F (1) met the mortar cube compressive strength, however, for control strands A-3, C-1, and C-4, multiple wires began to separate from the strand and king wire in multiple con. This error is typical when the tension clamps that grip the strand from below undergo substantial wear. The tension clamps were replaced and the mix was repeated.

Figure 5 displays a plot of the curing temperatures against the pull-out values for each control strand. A power regression was used to fit the data. The R^2 values are also displayed to show the strength of the correlation.

Pullout Load Values at 0.1" Slip (lbs)					
	Mix (Variable Cure Temperature)				
Mix Name	**64°F (1)**	**64°F (2)**	**73°F (1)**	**90°F (1)**	**90°F (2)**
Mix Cure Time (hr)	**25**	**26**	**24**	**20**	**14**
Mix Temperature (°F)	**64**	**64**	**73**	**90**	**90**
Water-Cement Ratio	**0.473**	**0.479**	**0.476**	**0.475**	**0.477**
Unit Weight (lb/ft^3)	**139.5**	**140.2**	**135.1**	**140.0**	**140.4**
Avg. Mortar Str. @ Test	**4,850 psi**	**4,704 psi**	**4,905 psi**	**5,873 psi**	**4,688 psi**
Strand 'A'					
A-1	14,400	14,200	15,900	16,900	13,400
A-2	14,600	12,300	14,700	17,900	18,000
A-3	-	11,900	15,700	18,400	16,000
A-4	17,000	13,000	14,700	16,200	17,000
Avg.	**15,333**	**12,850**	**15,250**	**17,350**	**16,100**
Std. Dev.	**1,447**	**1,008**	**640**	**988**	**1,977**
Strand 'C'					
C-1	-	8,000	10,600	10,200	9,400
C-2	4,900	8,000	8,700	9,200	8,300
C-3	6,500	7,900	8,700	7,900	10,900
C-4	-	7,300	9,100	7,800	9,200
Avg.	**5,700**	**7,800**	**9,275**	**8,775**	**9,450**
Std. Dev.	**1,131**	**337**	**903**	**1,144**	**1,079**
Strand 'J'					
J-1	14,200	19,400	19,100	25,000	19,200
J-2	14,700	17,800	21,400	24,500	17,100
J-3	15,200	17,200	16,500	23,100	20,600
J-4	15,000	14,900	17,000	22,000	23,500
Avg.	**14,775**	**17,325**	**18,500**	**23,650**	**20,100**
Std. Dev.	**435**	**1,864**	**2,238**	**1,363**	**2,685**

Table 7. Pull-Out values from modified STSB and mix properties for each curing temperature.

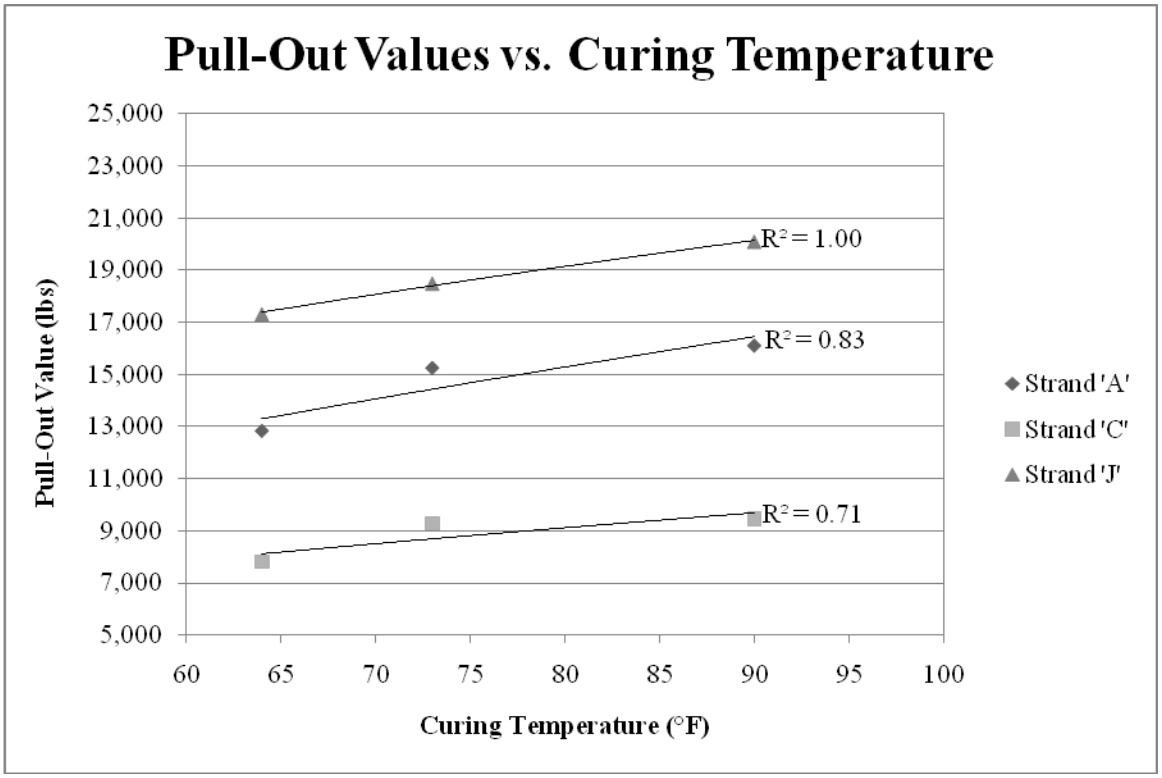


Figure 5. Pull-Out values from modified STSB plotted against curing temperature.

4.4 Trial Batching

In Tables 8 through 12, the average error and the standard deviation of the error from trial-batching are presented for 18, 24, 30, 48, and 72 hrs curing. f'_c represents the compressive strength of the mortar for the given w/c ratio, while $\bar{f}'_c$ represents the average of the three compressive strengths for each w/c ratio, and *r* represents the difference of f'_c and $\bar{f}'_c$. The average error is, as expected, 0, and the standard deviation, S_r, is shown for each curing time.

18 Hr				
n	**w/c**	f'_c	$\bar{f}'_c$	r
1	0.420	5273	5218	55.1
2	0.420	5308	5218	89.4
3	0.420	5304	5218	86.2
4	0.470	4154	4338	-183.5
5	0.470	4356	4338	18.6
6	0.470	4255	4338	-82.2
7	0.520	3433	3457	-23.7
8	0.520	3367	3457	-89.7
9	0.520	3368	3457	-88.9
10	0.575	2657	2576	80.7
11	0.575	2622	2576	45.3
12	0.575	2666	2576	89.7
			$\bar{x}_r$	0
			S_r	91.6

Table 8. Average error and standard deviation of error 18 hr trial batching mix.

24 Hr				
n	w/c	f'_c	$\bar{f}'_c$	r
1	0.420	5725	5676	49.9
2	0.420	5447	5676	-228.3
3	0.420	5844	5676	168.8
4	0.470	5096	4892	203.9
5	0.470	4958	4892	66.1
6	0.470	4953	4892	61.1
7	0.520	3794	4108	-314.1
8	0.520	3953	4108	-154.6
9	0.520	3948	4108	-159.9
10	0.575	3563	3324	238.4
11	0.575	3259	3324	-65.2
12	0.575	3461	3324	137.1
			$\bar{x}_r$	0
			S_r	181.1

Table 9. Average error and standard deviation of error 24 hr trial batching mix.

30 Hr				
n	w/c	f'_c	$\bar{f}'_c$	r
1	0.420	6272	6249	23.0
2	0.420	6493	6249	243.5
3	0.420	5921	6249	-328.6
4	0.470	5536	5438	98.4
5	0.470	5620	5438	181.8
6	0.470	-	-	-
7	0.520	4559	4627	-67.8
8	0.520	4465	4627	-161.7
9	0.520	4480	4627	-146.7
10	0.575	4074	3815	259.2
11	0.575	3946	3815	130.4
12	0.575	3582	3815	-233.1
			$\bar{x}_r$	0
			S_r	200.3

Table 10. Average error and standard deviation of error 30 hr trial batching mix.

48 Hr				
n	**w/c**	f'_c	$\bar{f}'_c$	r
1	0.420	7300	7247	53.2
2	0.420	6965	7247	-281.9
3	0.420	7652	7247	404.6
4	0.470	6335	6273	62.4
5	0.470	6329	6273	56.0
6	0.470	6043	6273	-230.3
7	0.520	5253	5299	-46.3
8	0.520	4976	5299	-322.6
9	0.520	5356	5299	57.3
10	0.575	4416	4325	90.6
11	0.575	4393	4325	68.1
12	0.575	4408	4325	83.5
			$\bar{x}_r$	0
			S_r	198.9

Table 11. Average error and standard deviation of error 48 hr trial batching mix.

72 Hr				
n	**w/c**	f'_c	$\bar{f}'_c$	r
1	0.420	8113	7820	293.4
2	0.420	7401	7820	-419.1
3	0.420	7926	7820	106.1
4	0.470	6550	6816	-265.8
5	0.470	7143	6816	327.5
6	0.470	6957	6816	141.6
7	0.520	5712	5812	-99.0
8	0.520	5641	5812	-170.8
9	0.520	5734	5812	-77.7
10	0.575	4761	4807	-46.0
11	0.575	4948	4807	140.4
12	0.575	4877	4807	69.8
			$\bar{x}_r$	0
			S_r	222.1

Table 12. Average error and standard deviation of error 72 hr trial batching mix.

CHAPTER 5

DISCUSSION OF RESULTS

5.1 Introduction

The results from the curing time and temperature test programs are discussed in this section. Plots of the STSB pull-out values were made against properties of the mortar and curing conditions. The pull-out values, w/c ratios, unit weights, curing time, and curing temperature data is presented in the previous chapter.

Batch weights for the mixtures were developed from the w/c ratio corresponding with the curing time to produce a mortar cube compressive strength of 4,750 ± 250 psi as specified by the STSB method. The pull-out values from the testing program were also compared to base pull-out values that were from previous tests for control strands A, C, and J. The base STSB pull-out values for the control strand under normal curing conditions, 24 hrs and 73°F, are presented in Table 13 along with the standard deviation and the number of samples. The values are reported in pounds (lbs).

Typical Pullout Load Values		Std. Dev.	# of Samples
Strand 'A'	**17,027**	**1,642**	**78**
Strand 'C'	**9,154**	**1,442**	**91**
Strand 'J'	**21,756**	**2,464**	**69**

Table 13. Base pull-out values for control strand (lbs).

5.2 Curing Time Test Results

The plot presented in Fig. 6 showed the average pull-out values against the w/c ratio from the curing time test program. A power regression was used to fit the data, and the R^2 value is displayed. For the higher bond strength control strand, such as A and J, the modified STSB produces significantly higher pull-out values for mixtures with w/c ratios less than 0.48. For mixtures with w/c ratios greater than 0.48, the pull-out values decrease nearly leveling off. Likewise, the results plotted in Fig. 4, after 30 hours of curing the rate of decrease for the pull-out values decrease and mixtures cured for less than 30 hours display and increase in pull-out values. The low bond strength control strand C displayed no such trend. Control strand C showed relatively little difference between curing for greater or less than 30 hours or in mixtures with a w/c ratio greater or less than 0.48.

Figure 7 plots the average pull-out values against the measured unit weight (lbs/ft^3) for each control strand. A power regression was used to fit the data which produced low correlation values. The measured unit weight was taken from the freshly mixed mortar. A 0.1 ft^3 unit weight/air content bucket was weigh the mortar. The results from the measured unit weight varied from the theoretical or calculated unit weight. The calculated unit weight is the weight from batch weight calculations from a mix based on a 1 ft^3. Figure 8 displays a plot of the average pull-out values against the calculated unit weight (lbs/ft^3) for each control strand. The R^2 values are also shown on the plot from power regressions. The data and the regressions from the calculated unit weight highlight a more intuitive result when plotted against the average pull-out values. This suggests perhaps the procedures and measurement of the fresh unit weight were inconsistent. Figure 15 illustrates the inconsistency between the measured unit weight and the calculated unit weight.

Considering Figs. 6 and 8, the trend for the higher bonding control strands would suggest that a denser mix produces higher pull-out values resulting from an evaluation of the actual bond strength of the strand. The w/c ratios can be related to the unit weight by the addition or subtraction of cement or water. Cement is roughly over three times denser than water, and when the w/c ratio is altered, the unit weight is affected. A lower w/c ratio corresponds to a higher unit weight.

Figures 9 through 11 displays the average pull-out values plotted against the w/c ratio for each control strand. A power regression is used to fit the data. In addition, R^2 values are displayed on the plots as well as a range of the base value for the specific control strands. The range of the base value for the control strands is 1 standard deviation (σ) from the average and is represented by the dashed lines. The trends from Figs. 9-11 match the trends from Fig. 8. As the density of the mixtures increase and the w/c ratio decrease, the pull-out values increase with a w/c ratio of approximately less than 0.50. W/C ratios greater than 0.50, will produce pull-out values that do not evaluate the bond strength of the strand accurately. Furthermore, mixtures cured for greater than 30 hrs, which relates to the w/c ratios previously mentioned and unit weight, will not produce meaningful pull-out data.

Figures 12 through 14 displays the average pull-out values plotted against the calculated unit weight for each control strand. A power regression trend line was used to fit the data, and the R^2 values are displayed on each figure. The dashed lines represent a range of the average ± 1σ of the base values for the respective control strands. The calculated unit weights were used instead of the measured unit weights due to the variability in the process of determining unit weight. The trends match the data and results from Figs. 9-11 where a lower w/c ratio produced higher pull-out values. As the density of the mixture increases, the pull-out values increase. This correlation is apparent only in the higher bond performing strand.

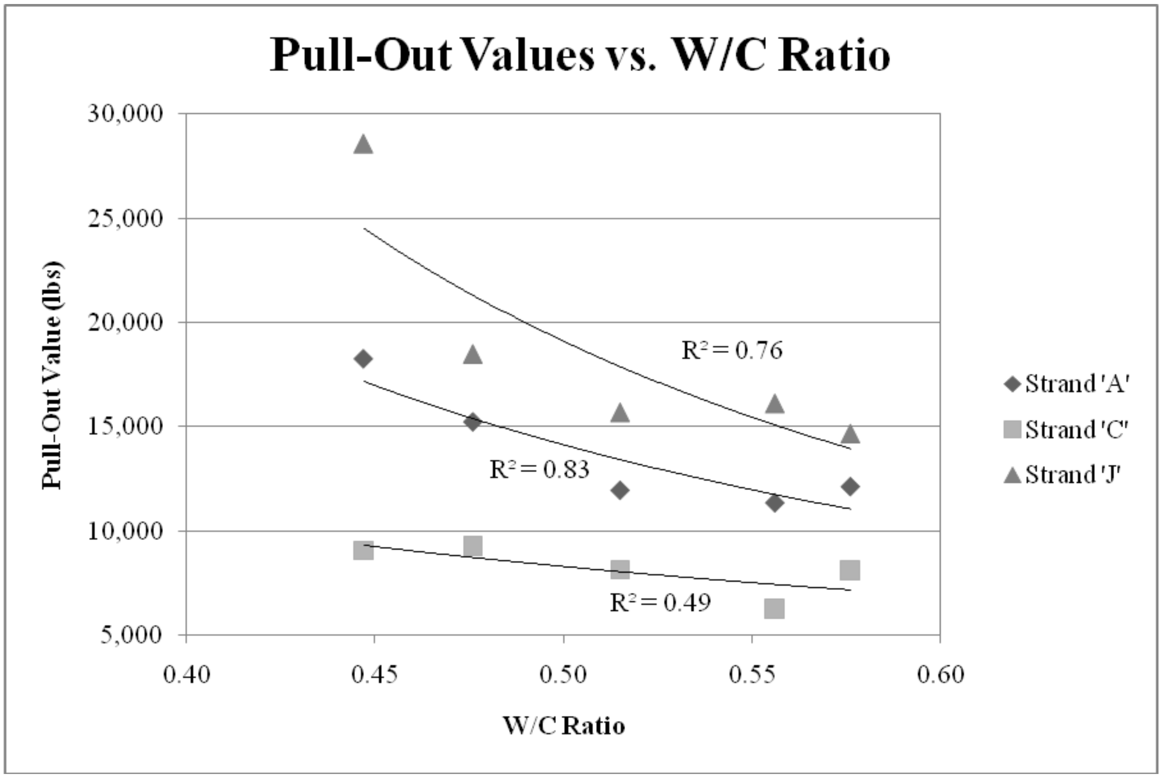


Figure 6. Average Pull-Out values from modified STSB plotted against w/c ratio.

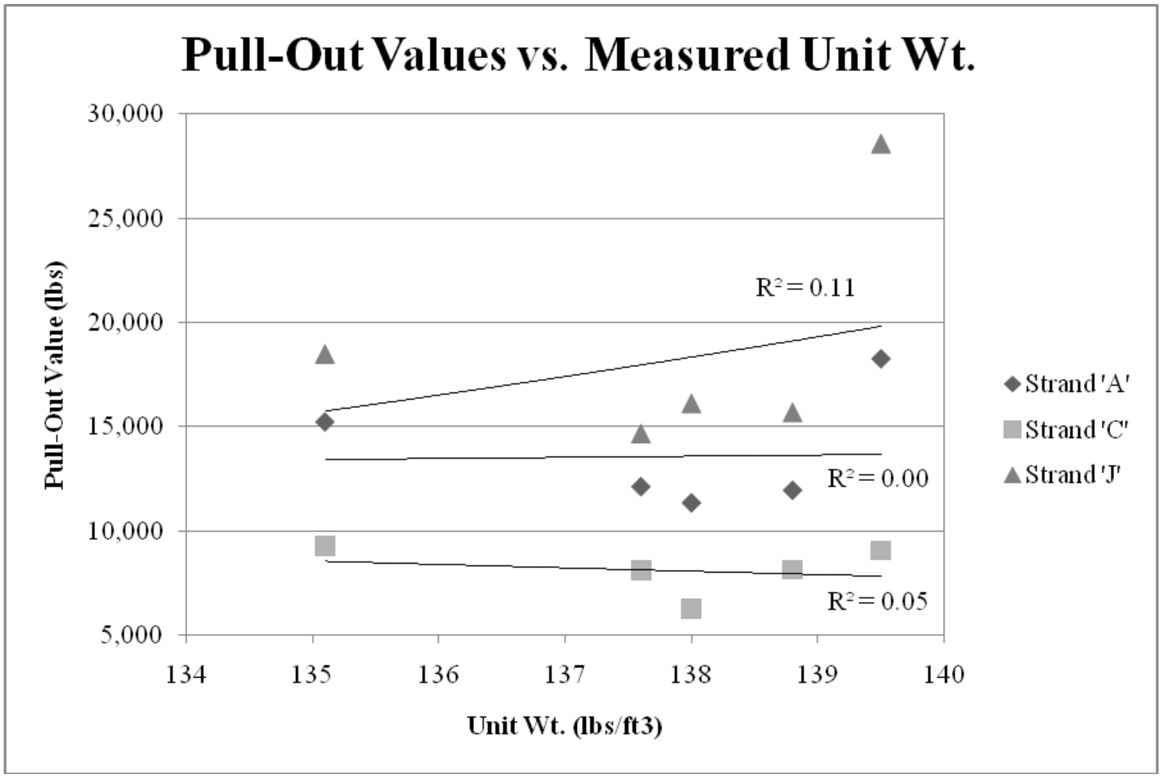


Figure 7. Average Pull-Out values from modified STSB plotted against measured unit wt.

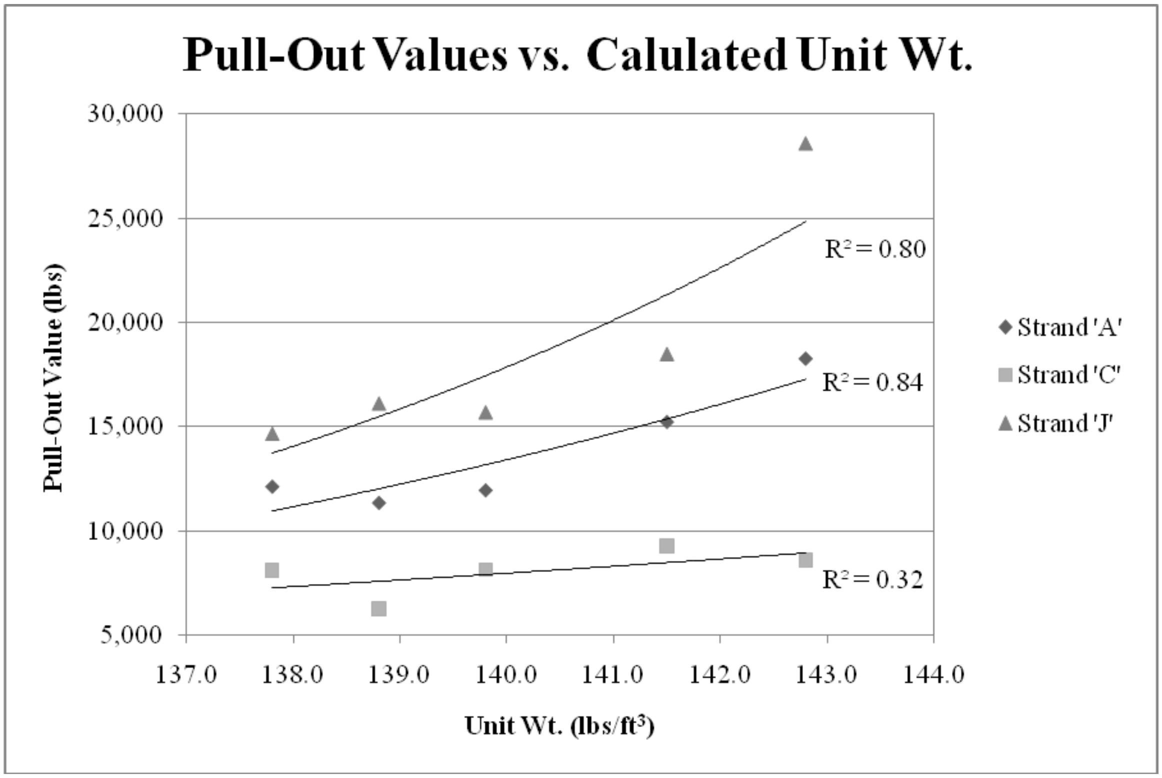


Figure 8. Average Pull-Out values from modified STSB plotted against curing time.

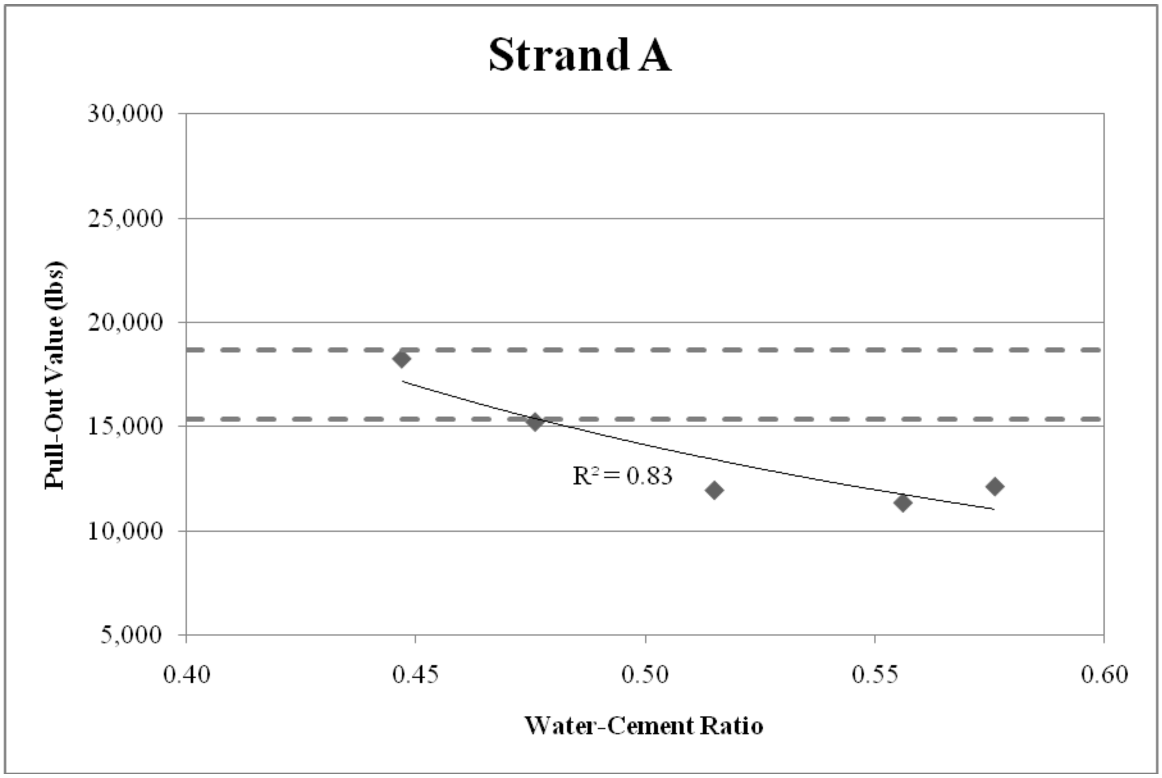


Figure 9. Average Pull-Out values from modified STSB plotted against w/c ratio for strand A.

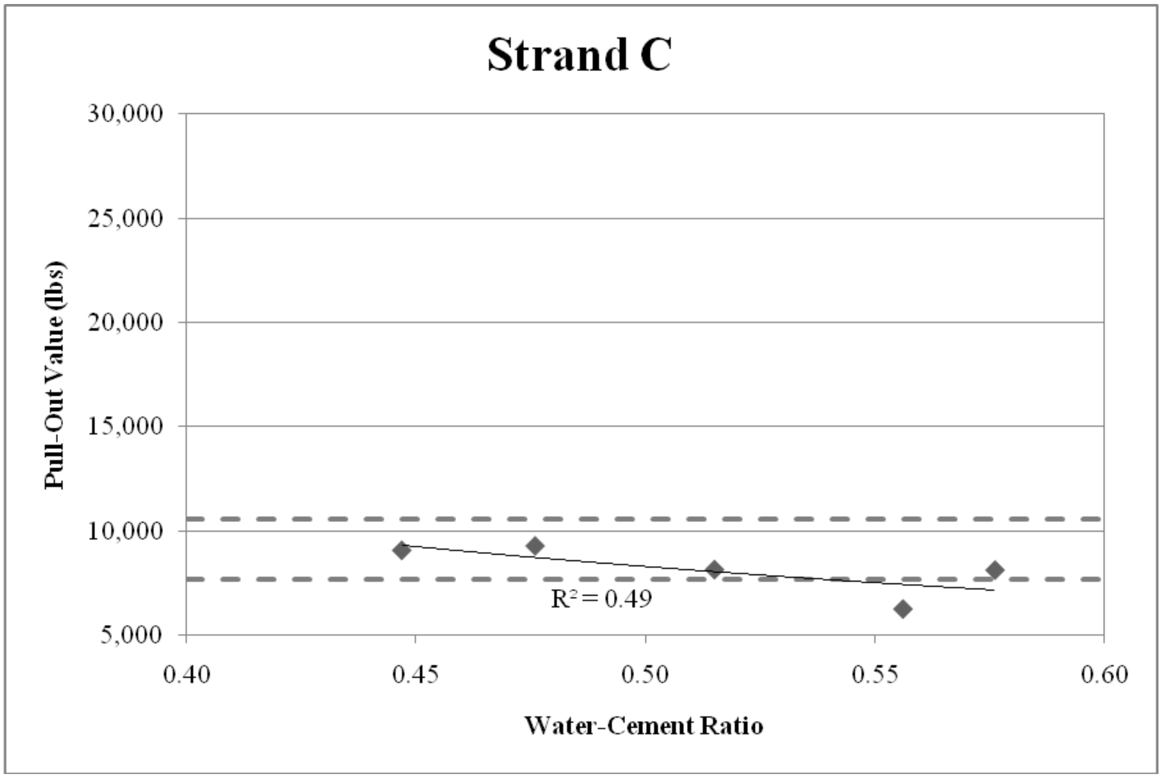


Figure 10. Average Pull-Out values from modified STSB plotted against w/c ratio for strand C.

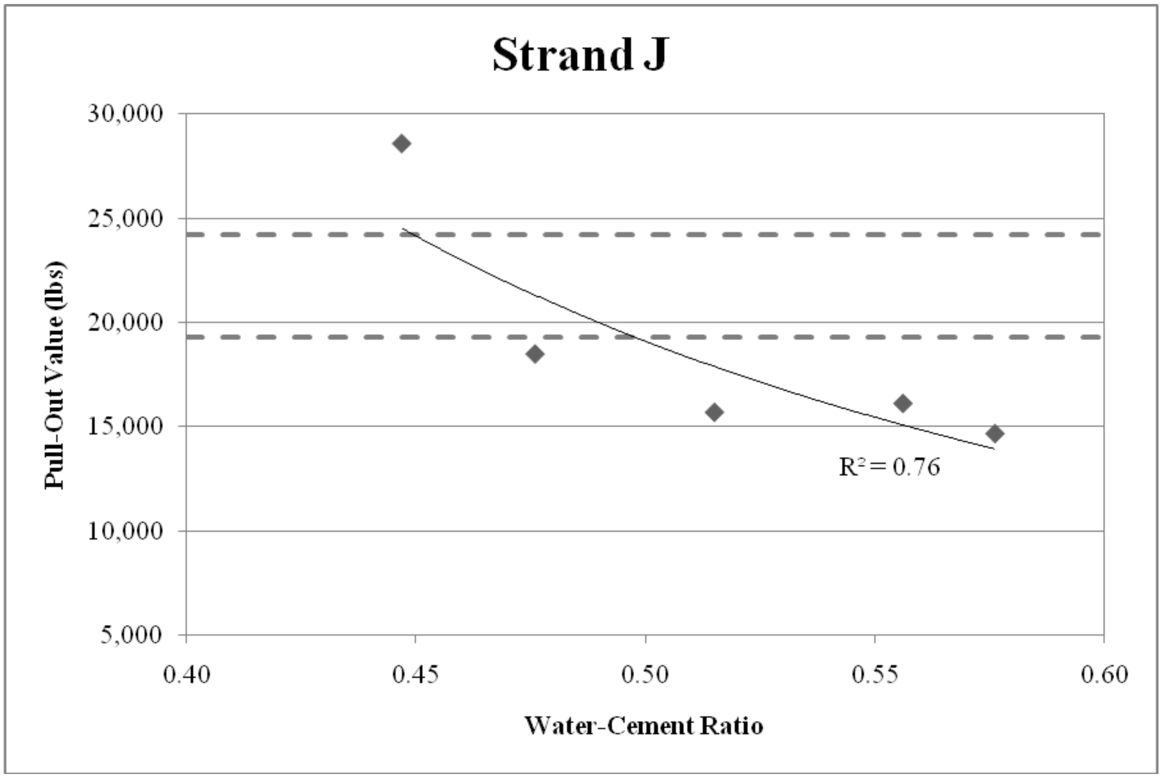


Figure 11. Average Pull-Out values from modified STSB plotted against w/c ratio for strand J.

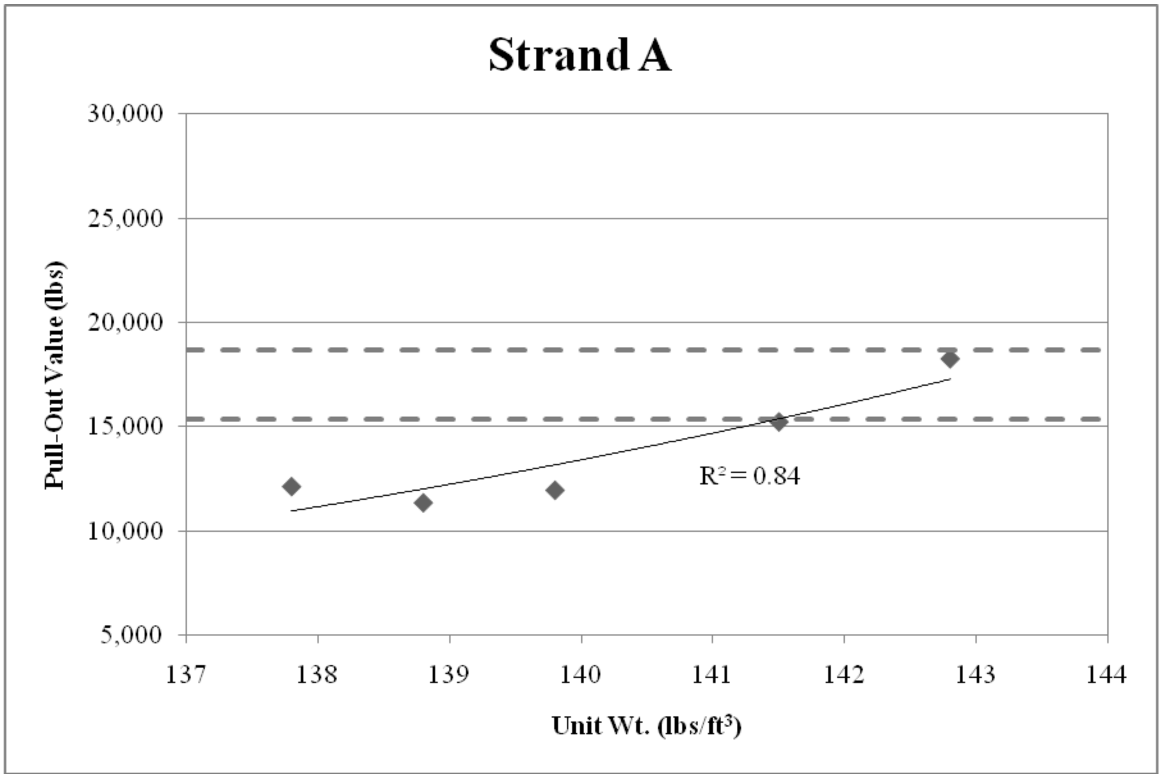


Figure 12. Average Pull-Out values from modified STSB plotted against unit weight for strand A.

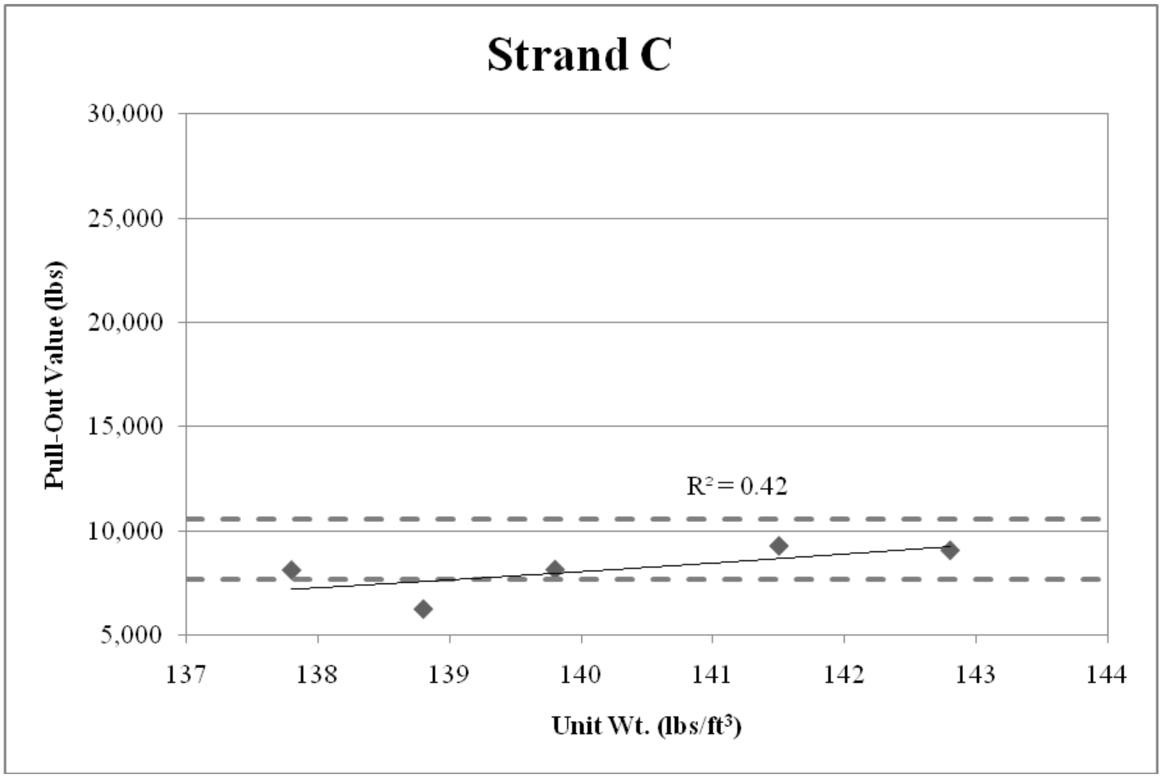


Figure 13. Average Pull-Out values from modified STSB plotted against unit weight for strand C.

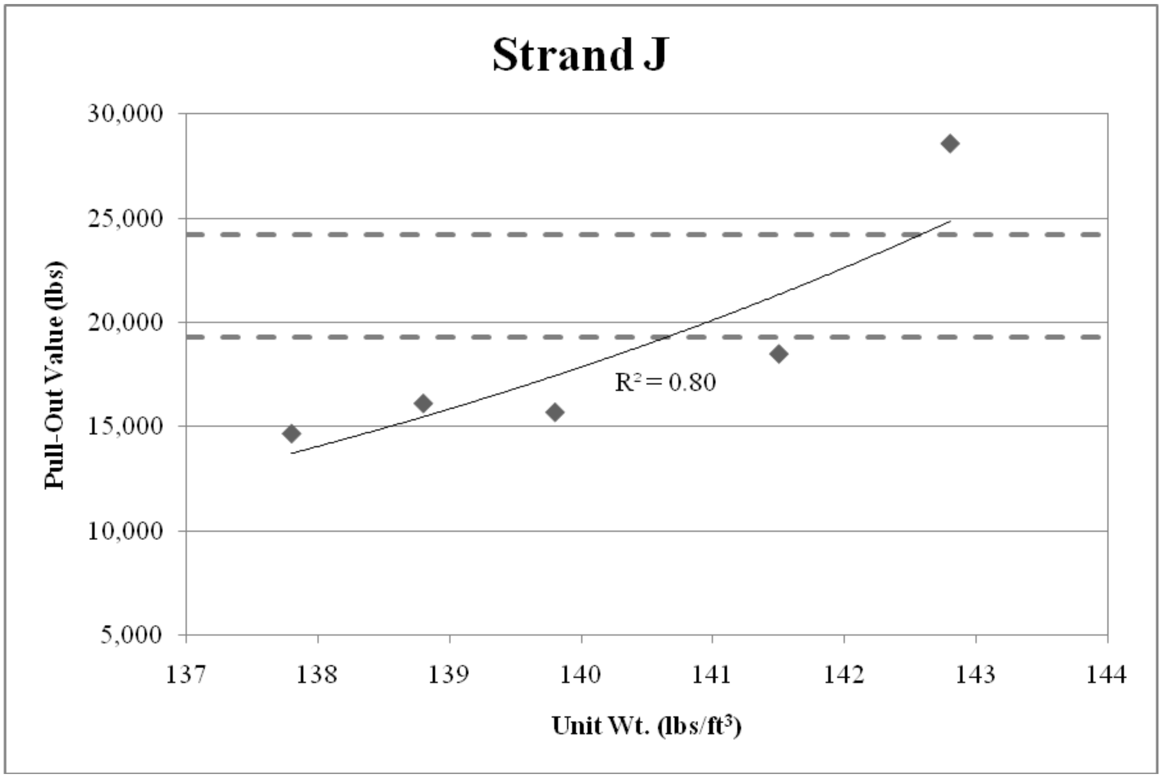


Figure 14. Average Pull-Out values from modified STSB plotted against unit weight for strand J.

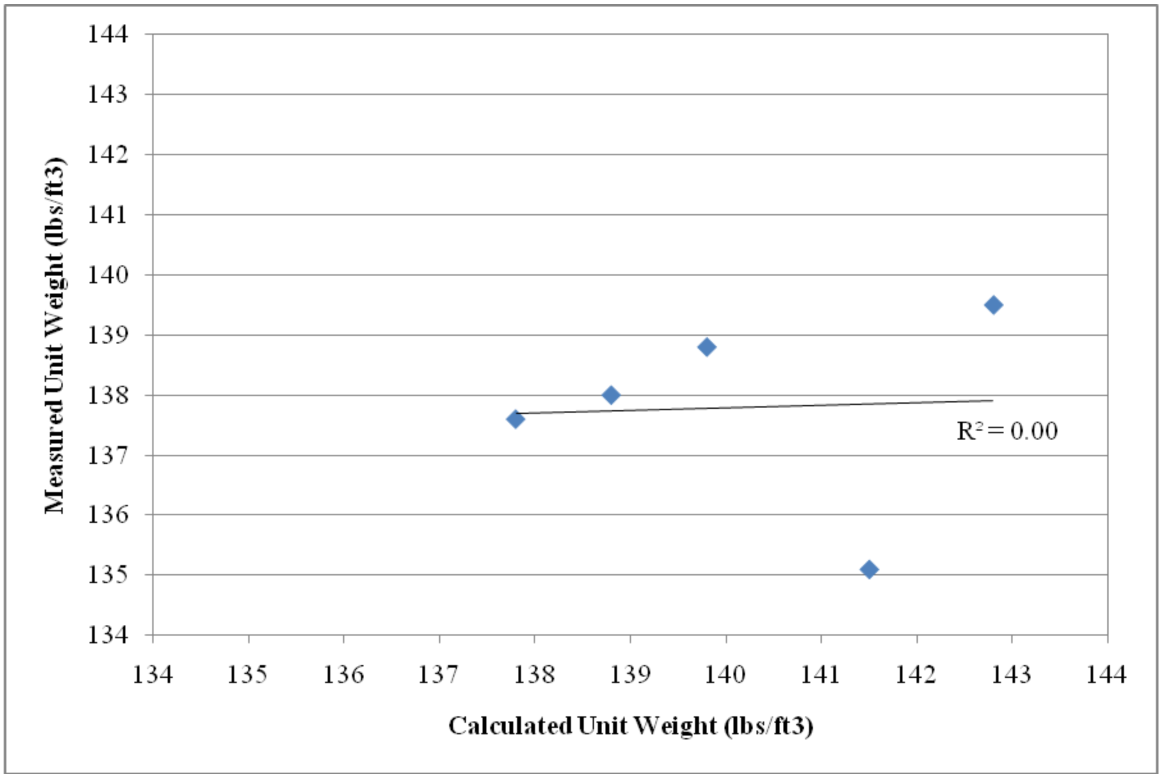


Figure 15. Calculated unit weight plotted against the measured fresh unit weight of the mortar.

5.3 Curing Temperature Test Results

Figure 16 displays the average pull-out values plotted against the curing temperature of each mix for each control strand. The R^2 value is also given to show the strength of the correlation. Figure 17 displays the average pull-out values plotted against the curing time of each mix for each control strand as well as the R^2 value. Both plots show power regressions. As expected, as the curing temperature increases the pull-out values increased, thus the high correlation values; however, with only three data points in a data series, high correlation values can be expected. As shown in Chapter 4, the mixtures had relatively the same mortar strengths, unit weights, and w/c ratios. Although there is relatively little variance in the pull-out values between temperature extremes, the data suggests a narrow range of curing temperatures from 73°F provides an environment for consistent results.

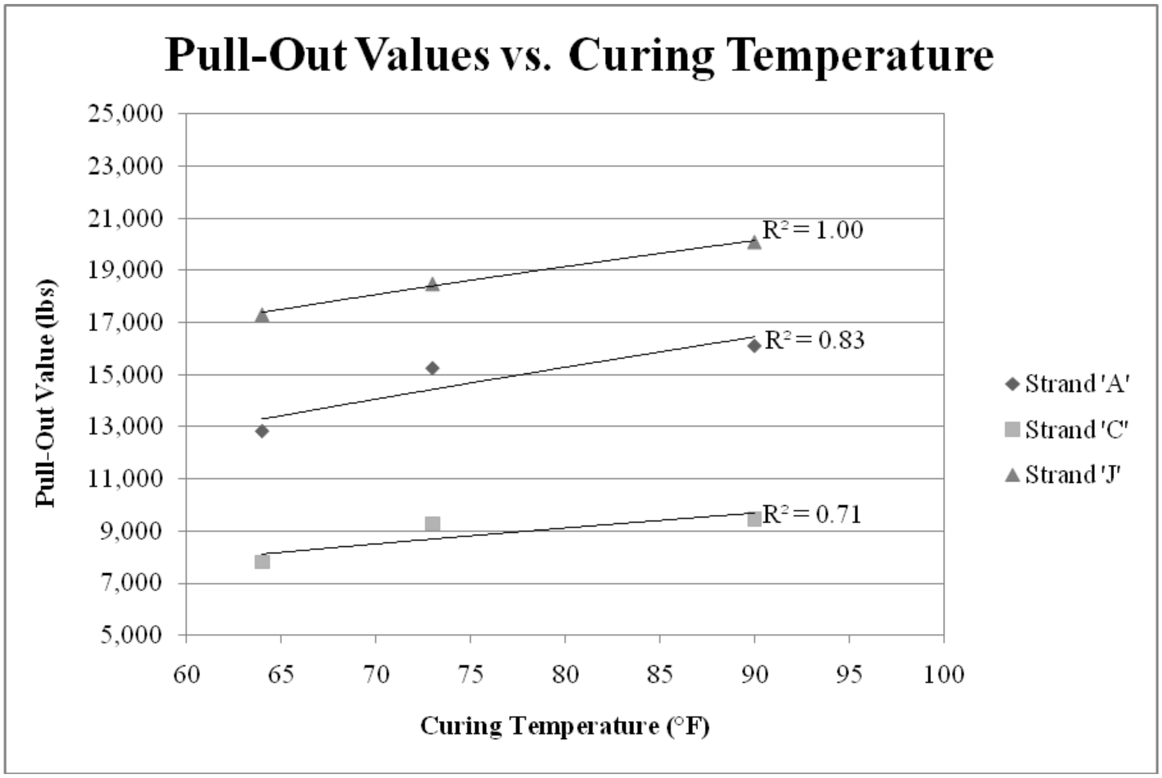


Figure 16. Average pull-out values plotted against curing temperature.

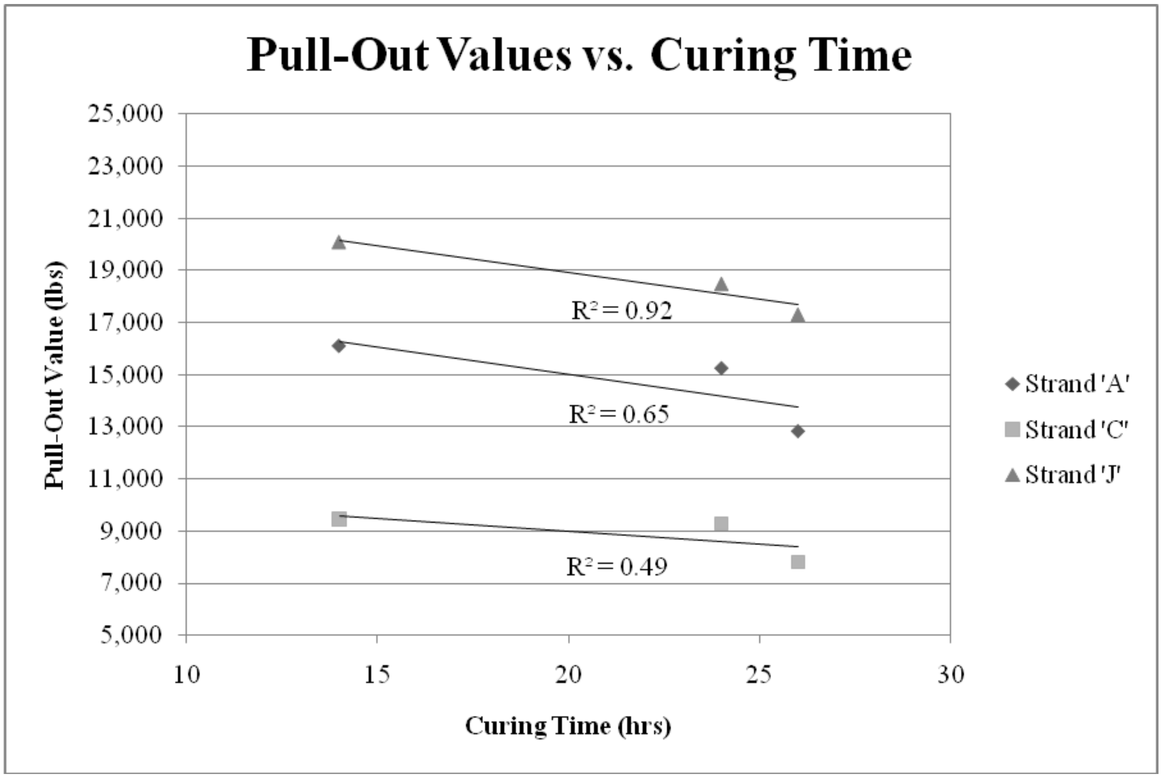


Figure 17. Average pull-out values plotted against curing time.

5.4 Trial Batching

Figure 18 plots the compressive strength of the mortar cubes from trial batching against the curing time. The cubes are in data series by w/c ratio and show strength gain with time. Power regression was used to fit the data and the R^2 values are displayed on the plot. Table 14 lists the power regression equations for each of w/c ratios.

The derivative of the power regressions was taken and the strength gain per hour in the mortar at times of 18, 24, 30, 48, and 72 hours is listed in Table 15 and plotted in Fig. 19. The derivative of the power equation, $y = Ax^b$, is $y = A*bx^{x-1}$. The rate of strength gain can be valuable when using the STSB and measuring the compressive strength in the mortar.

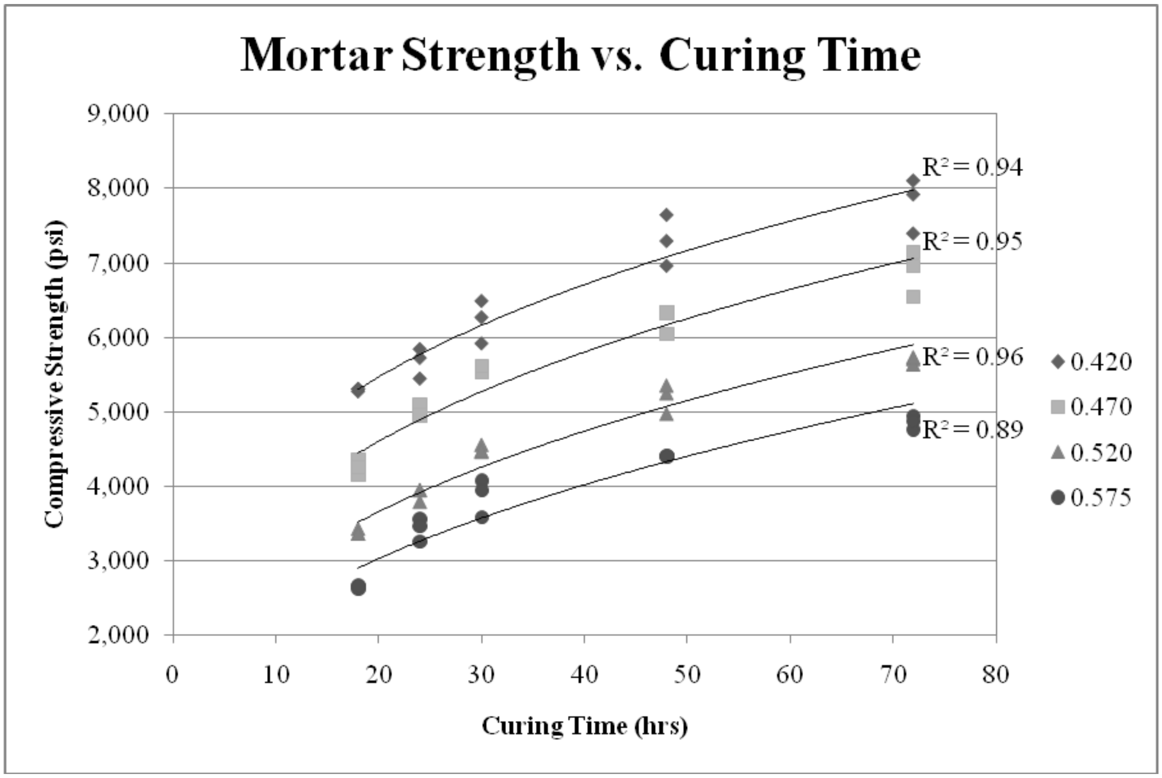


Figure 18. Mortar compressive strength from mortar cubes plotted against the curing time.

W/C	Power Regression Equations
0.420	$y = 2260.6x^{0.295}$
0.470	$y = 1695.5x^{0.334}$
0.520	$y = 1197.5x^{0.373}$
0.575	$y = 891.8x^{0.408}$

Table 14. Power regression equations.

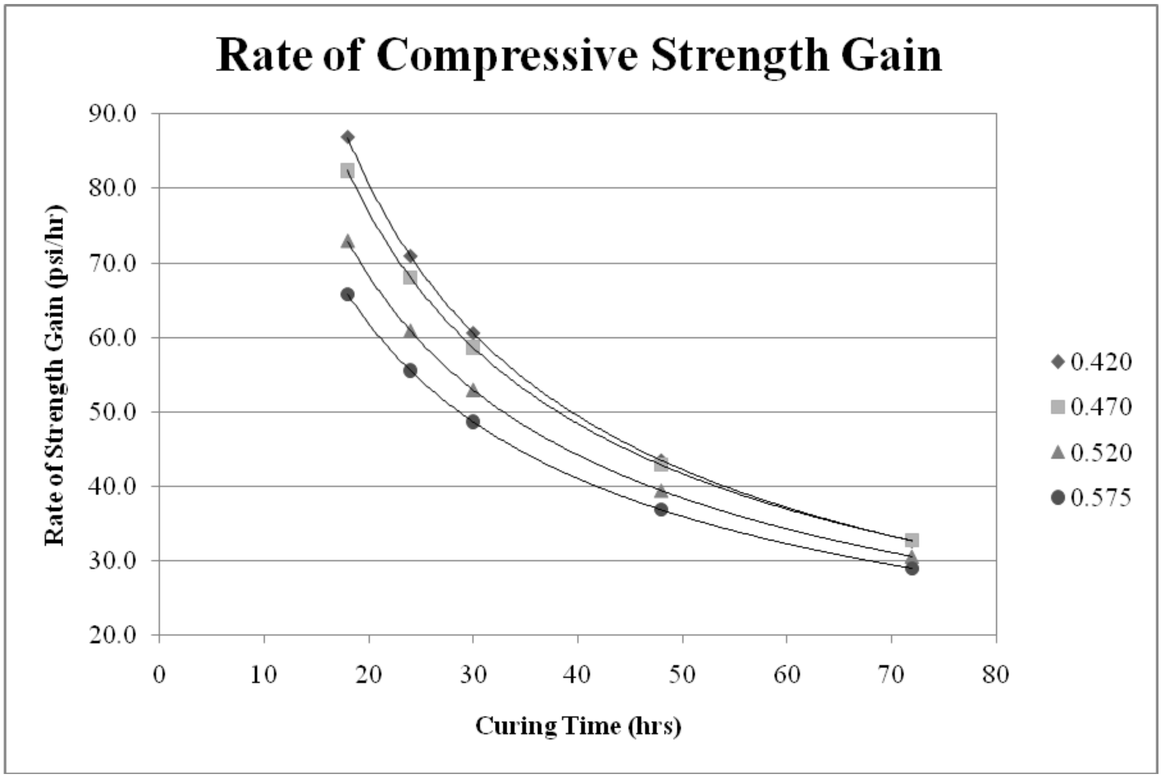


Figure 19. Rate of strength gain for trial-batching mortar cubes.

Rate of Compressive Strength Gain (psi/hr)					
W/C	**Curing Time**				
	18	**24**	**30**	**48**	**72**
0.420	86.9	70.9	60.6	43.5	32.7
0.470	82.4	68.0	58.6	42.9	32.7
0.520	72.9	60.9	52.9	39.4	30.6
0.575	65.8	55.5	48.7	36.9	29.0

Table 15. Rate of strength gain for trial-batching mortar cubes.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Introduction

The STSB method was used to test the effects of the curing environment on pull-out values. This was done two ways: (1) Altering the specified curing time to 18, 24, 30, 48, and 72 hours while maintaining the specified mortar strength at the time of testing by increasing or decreasing the w/c ratio and not using additives, and (2) Altering the specified curing temperature to 64°F and 90°F and testing at the time the specified mortar strength is reached. Each batch for every curing variable included four strands from each of the three control strand coils. The mortar used to fill the cylinders was required to meet compressive strength requirements to ensure the samples had relatively equal strengths at the time of testing. Pull-out values that correlate to bond strength were recorded and compared against previous pull-out vales from the well tested control strands.

The test results from altering the curing time showed an increase in pull-out values with a decrease in curing time. As mentioned before, the mortar strengths of the samples were the same, yet lower curing time and lower w/c ratios produced higher pull-out values. Plots of the pull-out values versus the calculated unit weight show a trend of higher unit weights produce higher pull-out values. Lower w/c ratios contain more cement which yields a denser mix. Results indicate the denser the mortar in the cylinders, intuitively, the higher the bond between the contents. The actual unit weights of the mixtures produced less consistent results than the calculated, especially in the case of the 24-hr (1) mix. This could be attributed to error in unit weight measurement. Entrapped air, unlevel filling, or excess material remaining on the outside of the pot, while weighing, could all potentially affect the unit weight. The differences between the calculated unit weights were minimal and any combination of mistakes could lead relatively substantial error.

The test results from altering the curing temperature demonstrated an increase in pull-out values with an increase in curing temperature. The variables known to affect the pull-out values were held constant except for the curing temperature. The mixtures for each of the variables were essentially the same, and the compressive strengths of the mortar were the relatively the same. The curing time needed for the samples cured at 90°F were substantially different; however, the calculated densities of the mixtures were relatively equal. The trends were consistent with each of the control strand and produced high R^2 values; however, comparing three data points in a series should produce high R^2 values.

6.2 Conclusions

Conclusions taken from the testing program include:

1) Mixtures must conform to the specified curing conditions and mixture properties for valid strand bond assessment.
2) Mixtures with lower w/c ratios demonstrated higher sensitivity to pull-out values in higher performing strand.
3) Higher unit weight mixtures from lower w/c ratios produce higher pull-out values.
4) Mixtures cured for times outside of the specified curing time, 24 ± 2 hrs, affects pull-out value results.
5) Pull-out values increase as the curing temperature is increased.
6) Storing samples in curing conditions outside of the requirements specified by the STSB will affect pull-out value results.

6.3 Recommendations

Recommendations from the testing program include:

1) Suggest w/c ratios of 0.48 or less to ensure denser mixtures and valid bond performance results.
2) Retain range of 73 ± 3°F for curing temperatures to ensure valid results from pull-out data from the STSB method.
3) Further explore the relationship between unit weight and pull-out values.
4) Develop a correlation between w/c ratio and pull-out values to adjust the acceptability criteria for the change in curing conditions.
5) Develop a correlation between curing temperature and pull-out values to adjust the acceptability criteria for the change in curing conditions.

REFERENCES

American Society for Testing and Materials (ASTM) (2003), “Annual Book of ASTM Standards 2003.” Volume 04.01 – 04.02.

Anderson, K.W., et al. (2009), “Use of the Maturity Method in Accelerated PCCP Construction.” Final Report WA 04-02. Washington State Department of Transportation, 52 pp.

Ramirez, J.A., Russell, B.W. (2007), “Transfer, Development, and Splice Length for Strand/Reinforcement in High-Strength Concrete.” Final Report NCHRP 12-60. National Cooperative Highway Research Program Transportation Research Board, 81 pp.

Russell, B.W. and Paulsgrove, G.A. (1999a), “NASP Strand Bond Testing Round One Pull-Out Tests and Friction Bond Tests of Untensioned Strand.” Final Report 99-03. The University of Oklahoma, Fears Structural Engineering Laboratory, 60 pp.

Russell, B.W. and Paulsgrove, G.A. (1999b), “Assessing Repeatability and Reproducibility of the Moustafa Test, the PTI Bond Test and the NASP Bond Test.” Final Report 99-04. The University of Oklahoma, Fears Structural Engineering Laboratory, 69 pp.

Russell, B.W. and Brown, M.D. (2004), “Final Report NASP Round III Evaluation of Test Methods in Assessing Bond Quality of Prestressing Strands,” North American Strand Producers Assoc., 301 pp.

Russell, B.W., (2006), “Final Report NASP Round IV Strand Bond Testing,” The Oklahoma Department of Transportation, 119 pp.

APPENDIX A

STANDARD TEST FOR STRAND BOND PROCEDURES

Standard Test Method to Quantify the Bonding Capacity of Steel Strand, Uncoated Seven-Wire for Prestressed Concrete

1. Scope

This test method is designed to quantify the bonding capacity of low-relaxation ASTM A416 seven-wire prestressed concrete steel strand with a standardized mortar. The bonding capacity determined by this test method is stated as the tensile force required to begin pulling the strand through the cured mortar in a cylindrical steel casing. The result of the test is the tensile force recorded on the live-end of the strand corresponding with the movement (i.e. slip) of the dead-end of the strand a cumulative distance of 2.5 mm (0.1 in).

2. Summary of Test Method

Six samples of seven-wire prestressing steel strand are selected from a single continuous length. Each of the six strand samples are individually cast in a steel cylinder casing with a standardized cement mortar. The strand is exposed on both ends of the cylinder with a designated live-end and dead-end. Once the cement mortar reaches a specified compressive strength, the cylinder with the embedded steel strand is loaded into a tensile test machine. The designated live-end of the steel strand is gripped by the tensile test machine and pulled away from the cylinder at a specified displacement rate. The tensile force on the live-end of the strand is measured along with the corresponding displacement of the dead-end. The test reports the live-end tensile force observed when the dead-end strand displacement reaches a cumulative 2.5 mm (0.10 in). The results of each sample in the set of six are reported individually and as an average.

3. Referenced Documents

3.1. ASTM Standards:

A 416 Standard Specification for Steel Strand, Uncoated Seven-Wire for Prestressed Concrete
C 33 Standard Specification for Concrete Aggregates
C 150 Standard Specification for Portland Cement
C 192 Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory
C 1437 Standard Test Method for Flow of Hydraulic Cement Mortar
C 305 Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency
C 109 Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)

4. Terminology

4.1. *strand* – all references to strand in this test method shall be interpreted to be ASTM A 416 low-relaxation seven-wire prestressed concrete strand.

4.2. *manufactured length* – a length of strand that when manufactured is heated and tensioned then subsequently water cooled to achieve low-relaxation properties in one continuous length.

4.3. *bond breaker* – a product wrapped around strand to prevent strand-to-concrete bond over the installed length. Styrofoam pipe insulation is commonly used for this purpose.

4.4. *mortar* – a mixture of cement, fine aggregate (i.e. sand) and water

4.5. *bond* – the adhesion of strand to concrete or mortar

4.6. *test specimen* – an assembly consisting of one steel casing, one sample of strand and mortar

5. Significance and Use

5.1. Prestressed concrete strand is used in pre-tensioned and post-tensioned concrete construction.

5.2. In prestressed concrete applications, the prestressed concrete strand is expected to transfer prestressing forces to the cementitous structural member via the adhesion (i.e. bond) of the exposed wire strand surfaces to the surrounding cementitous material.

5.3. The prestressed concrete strand manufacturing processes and subsequent handling and storage conditions can influence the final bonding capacity of the strand.

5.4. Prestressed concrete strand is used in construction applications with a variety of concrete mixtures. Developing tests and threshold values for the performance of the strand in each of these unique mixtures is impractical. The results from this test method must be interpreted and correlated with performance in concrete to provide the intended benefit.

6. Apparatus

6.1.

6.1.1. A dial gauge or position transducer capable of measuring a minimum of 2.54 mm (0.10 in) of displacement with a minimum 0.254 mm (0.010 in) precision.

6.1.2. A tensile test machine with the following functionality:

- 6.1.2.1. Controlled loading rate based on cross-head displacement
- 6.1.2.2. Concurrent data collection of both tensile load and dead-end strand displacement
- 6.1.2.3. Gripping device without torsional restraint

7. Sampling of strand

- 7.1. Six samples of prestressed concrete strand are needed for this test. Each sample shall be at least 81 centimeters (32 inches) long.
- 7.2. Samples shall be collected from the same reel of strand (typically 3 metric tons) or the same manufactured length of strand (typically 18 – 25 metric tons).
- 7.3. The surface condition of the strand samples must be representative of the strand intended for use in bonded applications. Care shall be taken to prevent the introduction of surface contaminants which may alter the bond performance of the strand. Some examples of contaminants to be avoided are oils, grease, surface rusting visible to the unaided eye, sand, shop dust, metal shavings, etc.

8. Mortar specifications

- 8.1. *Materials*
  - 8.1.1. *Sand* – The sand shall conform to ASTM C 33 requirements for fine aggregate.
  - 8.1.2. *Cement* – The cement shall conform to ASTM C 150 requirements for Type III cement.
  - 8.1.3. *Water* – The water shall be potable.
- 8.2. *Mortar mix proportions* – The mortar mix shall be made in conformance with ASTM C 192
- 8.3. *Mortar performance requirements* – The mortar shall be tested in conformance with ASTM C 192 with the following exceptions and additional requirements.
  - 8.3.1. *Slump* – No measurements required.
  - 8.3.2. *Air content* – No measurements required.
  - 8.3.3. *Flow* – Mortar flow shall be measured in accordance with the procedures in ASTM C 1437. The flow rate shall greater than or equal to 100 but not to exceed 125.
  - 8.3.4. *Strength* – Mortar strength shall be evaluated in conformance with ASTM C 109 using 51 millimeter (2 inch) mortar cubes. Before starting the test and after a minimum of 22 hours curing time, mean mortar cube strength must be $\geq$ 31 MPa (4,500 psi). During performance of the strand bond test and within 24 hours ± 2 hours of mortar mixing, mean mortar cube strengths shall be between 31 MPa (4,500 psi) and 34.5 MPa (5,000 psi). (NOTE 8.1)

NOTE 8.1 – The ability to consistently achieve the specified mortar strengths can be a challenge for testing facilities with limited mortar experience and/or limited mixing and curing facilities. If mean mortar strengths are less than the 31 MPa (4,500 psi) when the strand bond test is performed, the strand bond test results will be biased to provide lower bond test values than if the mortar was within the specified range. For the purpose of comparing the bond test results of this test method against a minimum threshold value, a bond test result that exceeds a minimum threshold value with a mean mortar strength less than 31 MPa (4,500 psi) should be accepted as meeting a specified minimum threshold value.

If mortar strengths are greater than the 34.5 MPa (5,000 psi) when the strand bond test is performed, the strand bond test results will be biased to provide higher bond test values than if the mortar was within the specified range. For the purpose of comparing the bond test results of this test method against a minimum threshold value, a bond test result that is below a minimum threshold value with a mean mortar strength greater than 34.5 MPa (5,000 psi) should be considered as failing to meet the specified minimum threshold value.

9. Preparation of test specimens

9.1. *Materials*

9.1.1. *Strand samples* – Strand sample properties are defined in section 7.

9.1.2. *Mortar* – Mortar properties are defined in section 8.

9.1.3. *Bond breaker* – A 25 mm ± 6 mm (1 in ± ¼ in) outside diameter x 51 mm ± 2 mm (2 in ± 5/64 in) length section of pipe insulation or equivalent material shall be used as a bond breaker. The position of the bond breaker shall be as defined in Figure B1. (NOTE 9.1)

9.1.4. *Steel casing* - Each individual test specimen of strand shall be cast in a 125 mm (5 in.) outside diameter steel casing as defined in Figure B1. The thickness of the cylindrical walls of the steel casing shall not be less than 3.175 mm (0.125 in.) The other dimensions of the steel casing and the strand are indicated on the diagram. The steel casing shall have sufficient rigidity to prevent radial cracking visible to the unaided eye in the concrete mortar during testing.

9.2. *Sample assembly* – Each individual test specimen shall be made by casting one single strand concentrically in the steel casing with the mortar. The test specimen shall be cast with the longitudinal axis of the strand and the steel casing in the vertical position. Temporary jigs shall be used to keep the strand sample concentrically centered in the steel casing and to prevent longitudinal movement during mortar installation and consolidation. The temporary jigs can be removed after the mortar has cured and prior to testing.

9.3. *Consolidation* – After the cylinder is approximately 50% filled with mortar, the test specimens shall be mechanically consolidated by vibration in conformance with ASTM C 192. The mortar shall be consolidated to ensure that a normal amount of air voids exist at the interface between the strand and the surrounding concrete mortar. Excessive air voids can cause erroneous test results because air voids reduce the available bonding surface between the concrete mortar and the strand. Once the initial addition of mortar is consolidated, the next 40% of mortar shall be added to the steel casing and again mechanically consolidated by vibration in conformance with ASTM C 192. Once the mortar is consolidated the second time, the remaining 10% of mortar shall be added to the steel casing until a smooth, level mortar surface is achieved at the top of the casing.

9.4. *Curing* – Once all six sample test specimens and mortar cubes have been cast, curing of the mortar shall occur in conformance with ASTM C 192. The concrete mortar shall be cured in a controlled environment with the following conditions:

9.4.1. *Curing temperature* – Curing temperatures shall be 23°C ± 2°C (73°F ± 3°F).

9.4.2. *Curing relative humidity* – Average hourly relative humidity during curing must be maintained above 90.0%.

9.4.3. *Vibration* – The test specimens must be cured in an environment free of vibrations.

NOTE 9.1 – Variances in the length of the bond breaker can cause significant variance in the results of this test method. Careful attention to the dimensions, installation and position of the bond breaker during and after the addition of the mortar is essential.

10. Test Set-up

10.1. *Test Frame* – The test specimens shall be placed into the test frame with the capabilities as defined in section 6. The load shall be measured as applied to the live-end.

10.2. *Free-end slip measurement* – A position transducer or dial gauge shall be installed capable of measuring the movement of the dead-end of the strand relative to the hardened mortar or the steel casing. Figure B1 shows an example of one type of measurement apparatus. The measuring device shall measure dead-end strand movement as observed by movement of the center wire only.

10.3. *Strand gripping* – The strand shall be gripped by a chucking device capable of uniformly pulling all seven-wires of the strand. The free length between the bottom plate of the steel casing housing the specimen and the gripping device shall be sufficiently long to allow for gripping the strand. The strand gripping device shall not be restrained from torsional movement.

11. Test Procedure

11.1. *Test conditions* – The specimens can be removed from the controlled curing chamber and tested when both of the following 2 parameters are satisfied:

11.1.1. *Time* - 24 hours ± 2 hours of casting the specimens (NOTE 11.1)

11.1.2. *Mortar Strength* – Within the strength range specified in section 8.3.4.

11.2. *Mortar strength* – Mortar strengths shall be tested at the beginning of the test and at the end of the test. If the mean mortar strength exceeds 5,000 psi after the sixth sample is tested, the test is invalid.

11.3. *Displacement rate* – Load (i.e. pull-out force) shall be applied to the strand by displacement of the gripping device. The displacement rate shall be 2.5 mm/minute ± _0.127__ mm/min (0.1 in/min ± __0.005_ in/min). As load is applied to the strand, some seating of the gripping device or other test frame deflection is possible. These seating actions should be visibly smooth and not subject to sudden releases of energy. (NOTE 11.2)

11.4. *Test result* – The load (i.e pull-out force) rounded up to the nearest 10 lbf shall be recorded at the moment the dead-end of the strand has moved down into the mortar a cumulative total of 2.5 mm (0.10 in) by the application of force on the live-end. (NOTE 11.3)

NOTE 11.1 – Current research is investigating the importance of this time constraint. In the future, it is possible this time constraint may be extended to allow more time to complete the testing.

NOTE 11.2 – The loading rate of the sample is specified as a given rate of live-end displacement. During the development of this test method, strand loading rates in terms of force were also monitored and recorded concurrently with the displacement loading rates. Force loading rates between ____ lbs/min and ____ lbs/min were observed with strands of various bonding capacities between 7,000 lbf up to 25,000 lbf. Factors such as variances in test frame stiffness and gripping differences may cause higher or lower force loading rates with an unknown effect on the results of this test. If a test set-up generates loading rates outside of the range listed, the results of the tests may be affected and the observed force loading rates should be reported.

NOTE 11.3 – If the hardened concrete mortar exhibits cracking visible to the unaided eye in two or more of the six test specimens, the entire batch of six specimens shall be discarded and new specimens prepared.

12. Report

12.1. Identification of the strand tested (i.e. pack or reel number)

12.2. Date of original strand manufacture

12.3. Dates of test

12.4. Size of strand

12.5. Grade of Strand

12.6. Average pull-out force as defined in section 10.3 of the six specimens tested

12.7. Minimum pull-out force observed among the six specimens tested

12.8. Average of beginning and ending mortar strengths.

13. Precision and Bias

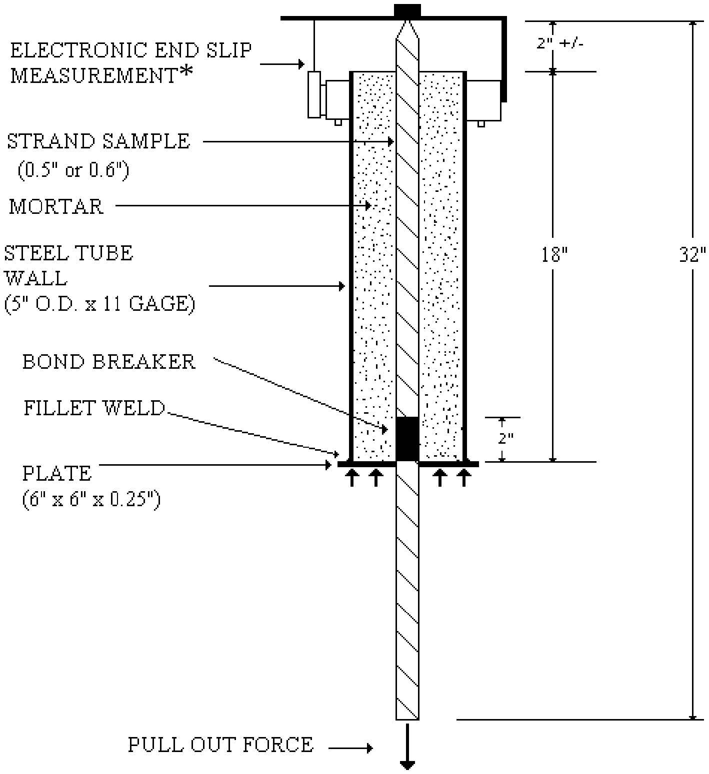
13.1. No statement is made on the precision and bias of these test methods since the test results indicate only whether there is conformance to given criteria and no generally accepted method for determining precision of this test method is currently available. General guidelines provided herein for the specimens, instrumentation, and procedures make the results intractable to calculation of meaningful values by statistical analysis for precision at this time.

13.2. Bias---Since there is no accepted reference material suitable for determining the bias in this test method, no statement on bias is made.

14. Keywords:

bond, strand

Figure B1 – Longitudinal Cross-section Diagram of Strand Sample in a Mortar-filled Cylinder



*The "Electronic End Slip Measurement" apparatus shown here is an example of one type of measurement set-up. Other configurations and devices can be used.

APPENDIX B

PULL-OUT VALUES FROM MODIFIED STSB

APPENDIX B
LIST OF TABLES

Mixture(s) : 24-HR (1)
Date : 7/1/2009

#	Axial Load (lbs) @ 0.02" Slip	Axial Load (lbs) @ 0.2" Slip
C-1	9,700	10,600
C-2	8,400	8,700
C-3	7,900	8,700
C-4	9,000	9,100
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
A-1	10,500	15,900
A-2	10,400	14,700
A-3	10,700	15,700
A-4	9,300	14,700
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
J-1	16,500	19,100
J-2	18,700	21,400
J-3	15,200	16,500
J-4	15,500	17,000

Table B1. Pull-out values from modified STSB for mixture 24-hr (1).

Mixture(s) : 18-HR (1)
Date : 7/8/2009

#	Axial Load (lbs) @ 0.02" Slip	Axial Load (lbs) @ 0.2" Slip
C-1	10,000	9,700
C-2	9,300	8,300
C-3	9,200	8,700
C-4	8,400	7,400
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
A-1	11,900	17,900
A-2	11,600	19,600
A-3	10,800	17,300
A-4	12,600	18,800
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
J-1	20,100	26,000
J-2	22,700	27,900
J-3	20,900	25,400
J-4	21,300	26,400

Table B2. Pull-out values from modified STSB for mixture 18-hr (1).

Mixture(s) : 72-HR (1)
Date : 7/13/2009

#	Axial Load (lbs) @ 0.02" Slip	Axial Load (lbs) @ 0.2" Slip
C-1	7,700	8,000
C-2	7,300	8,200
C-3	7,200	7,600
C-4	6,300	8,000
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
A-1	7,500	10,100
A-2	8,000	10,200
A-3	8,100	11,500
A-4	8,200	11,100
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
J-1	13,500	14,700
J-2	13,300	15,400
J-3	13,800	16,200
J-4	12,200	13,800

Table B3. Pull-out values from modified STSB for mixture 72-hr (1).

Mixture(s) : 48-HR (1)
Date : 7/19/2009

#	Axial Load (lbs) @ 0.02" Slip	Axial Load (lbs) @ 0.2" Slip
C-1	7,700	6,600
C-2	6,400	5,000
C-3	8,000	7,200
C-4	7,200	6,400
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
A-1	8,000	9,600
A-2	7,400	8,200
A-3	8,100	8,900
A-4	7,300	8,900
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
J-1	12,100	12,000
J-2	12,800	12,600
J-3	13,000	13,900
J-4	13,400	13,300

Table B4. Pull-out values from modified STSB for mixture 48-hr (1).

Mixture(s) : 48-HR (2)
Date : 7/22/2009

#	Axial Load (lbs) @ 0.02" Slip	Axial Load (lbs) @ 0.2" Slip
C-1	6,900	6,600
C-2	6,800	6,500
C-3	6,700	6,100
C-4	6,500	5,900
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
A-1	5,800	11,200
A-2	7,300	11,200
A-3	8,300	11,700
A-4	8,400	11,400
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
J-1	14,400	17,000
J-2	13,200	15,000
J-3	14,100	15,700
J-4	13,800	16,800

Table B5. Pull-out values from modified STSB for mixture 48-hr (2).

Mixture(s) : 18-HR (2)
Date : 7/23/2009

#	Axial Load (lbs) @ 0.02" Slip	Axial Load (lbs) @ 0.2" Slip
C-1	9,400	8,300
C-2	9,500	9,600
C-3	6,800	-
C-4	9,900	9,300
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
A-1	8,900	17,000
A-2	10,200	17,200
A-3	13,600	19,700
A-4	12,000	19,200
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
J-1	24,800	28,200
J-2	22,900	27,800
J-3	25,400	29,500
J-4	23,600	28,900

Table B6. Pull-out values from modified STSB for mixture 18-hr (2).

Mixture(s) : 72-HR (2)

Date : 7/27/2009

#	Axial Load (lbs) @ 0.02" Slip	Axial Load (lbs) @ 0.2" Slip
C-1	8,100	9,000
C-2	6,400	6,800
C-3	7,900	8,800
C-4	7,900	7,900
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
A-1	7,700	10,200
A-2	7,500	11,900
A-3	9,200	12,700
A-4	9,200	13,800
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
J-1	11,700	14,500
J-2	11,600	14,500
J-3	12,500	15,400
J-4	11,000	14,300

Table B7. Pull-out values from modified STSB for mixture 72-hr (2).

Mixture(s) : 30-HR (1)
Date : 7/29/2009

#	Axial Load (lbs) @ 0.02" Slip	Axial Load (lbs) @ 0.2" Slip
C-1	8,300	8,700
C-2	6,100	8,500
C-3	7,200	8,400
C-4	6,700	7,000
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
A-1	7,600	10,800
A-2	7,900	11,500
A-3	9,700	12,400
A-4	8,300	13,200
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
J-1	13,500	15,200
J-2	13,700	16,600
J-3	13,400	15,200
J-4	13,500	15,800

Table B8. Pull-out values from modified STSB for mixture 30-hr (1).

Mixture(s) : 64°F (1)
Date : 8/27/2009

#	Axial Load (lbs) @ 0.02" Slip	Axial Load (lbs) @ 0.2" Slip
C-1	5,800	-
C-2	5,600	4,900
C-3	7,000	6,500
C-4	-	-
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
A-1	9,700	14,400
A-2	8,200	14,600
A-3	5,800	-
A-4	5,700	17,000
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
J-1	12,600	14,200
J-2	12,900	14,700
J-3	13,500	15,200
J-4	13,400	15,000

Table B9. Pull-out values from modified STSB for mixture 64°F (1).

Mixture(s) : 64°F (2)
Date : 9/3/2009

#	Axial Load (lbs) @ 0.02" Slip	Axial Load (lbs) @ 0.2" Slip
C-1	7,800	8,000
C-2	7,600	8,000
C-3	7,800	7,900
C-4	6,600	7,300
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
A-1	8,600	14,200
A-2	8,500	12,300
A-3	9,600	11,900
A-4	9,600	13,000
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
J-1	16,300	19,400
J-2	16,100	17,800
J-3	14,800	17,200
J-4	13,000	14,900

Table B10. Pull-out values from modified STSB for mixture 64°F (2).

Mixture(s) : 90°F (1)
Date : 9/18/2009

#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
C-1	9,100	10,200
C-2	8,900	9,200
C-3	8,200	7,900
C-4	7,800	7,800
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
A-1	8,300	16,900
A-2	9,400	17,900
A-3	10,700	18,400
A-4	9,600	16,200
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
J-1	18,200	25,000
J-2	19,500	24,500
J-3	18,100	23,100
J-4	17,800	22,000

Table B11. Pull-out values from modified STSB for mixture 90°F (1).

Mixture(s) : 90°F (2)
Date : 9/22/2009

#	Axial Load (lbs) @ 0.02" Slip	Axial Load (lbs) @ 0.2" Slip
C-1	7,800	9,400
C-2	7,200	8,300
C-3	9,100	10,900
C-4	8,500	9,200
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
A-1	8,500	13,400
A-2	10,600	18,000
A-3	10,800	16,000
A-4	10,700	17,000
#	**Axial Load (lbs) @ 0.02" Slip**	**Axial Load (lbs) @ 0.2" Slip**
J-1	16,300	19,200
J-2	14,200	17,100
J-3	17,000	20,600
J-4	19,500	23,500

Table B12. Pull-out values from modified STSB for mixture 90°F (2).

APPENDIX C

MOISTURE CONTENT CALCULATIONS FOR MIXTURES

APPENDIX C
LIST OF TABLES

Mixture(s) : 48, 72 hr/0.420, 0.470
Date : 6/16/2009

Pan #	Pan Wt. (g)	Pan & Sample Wt. (g)	OD-Pan & Sample Wt. (g)	Moisture Content (%)
1	158.8	655.8	640.5	3.18
2	117.9	622.1	606.8	3.13
3	150.7	649.9	634.7	3.14
4	201.0	704.0	689.8	2.91
5	177.2	677.5	662.7	3.05
6	281.1	780.2	767.1	2.70
7	293.3	791.2	779.5	2.41
8	190.0	689.5	674.4	3.12

Table C1. Moisture Corrections from Trial Batching.

Mixture(s) : 18, 24, 30 hr/0.420, 0.470
Date : 6/17/2009

Pan #	Pan Wt. (g)	Pan & Sample Wt. (g)	OD-Pan & Sample Wt. (g)	Moisture Content (%)
1	158.9	659.7	649.2	2.14
2	117.9	619.9	606.4	2.76
3	150.8	658.0	640.8	3.51
4	201.1	700.1	686.6	2.78
5	-	-	-	-
6	281.1	776.9	763.8	2.71
7	293.4	797.5	785.4	2.46
8	-	-	-	-

Table C2. Moisture Corrections from Trial Batching.

Mixture(s) : 48, 72 hr/0.520, 0.575

Date : 6/23/2009

Pan #	**Pan Wt. (g)**	**Pan & Sample Wt. (g)**	**OD-Pan & Sample Wt. (g)**	**Moisture Content (%)**
1	158.9	658.2	644.5	2.82
2	118.0	616.6	602.3	2.95
3	150.7	651.2	637.8	2.75
4	201.0	699.1	687.3	2.43
5	177.2	674.6	665.2	1.93
6	281.1	785.3	775.5	1.98
7	-	-	-	-
8	-	-	-	-

Table C3. Moisture Corrections from Trial Batching.

Mixture(s) : 18, 24, 30 hr/0.520, 0.575

Date : 6/24/2009

Pan #	**Pan Wt. (g)**	**Pan & Sample Wt. (g)**	**OD-Pan & Sample Wt. (g)**	**Moisture Content (%)**
1	158.8	657.3	641.5	3.27
2	118.0	617.2	598.9	3.81
3	150.8	651.3	634.0	3.58
4	-	-	-	-
5	177.2	679.8	666.9	2.63
6	-	-	-	-
7	293.3	795.1	778.8	3.36
8	-	-	-	-

Table C4. Moisture Corrections from Trial Batching.

Mixture(s) : 24-hr (1)
Date : 6/30/2009

Pan #	Pan Wt. (g)	Pan & Sample Wt. (g)	OD-Pan & Sample Wt. (g)	Moisture Content (%)
1	158.8	654.3	645.5	1.81
2	118.0	614.5	603.4	2.29
3	150.8	650.3	638.0	2.52
4	200.9	700.4	687.5	2.65
5	177.1	677.5	664.3	2.71
6	-	-	-	-
7	293.2	795.2	781.7	2.76
8	190.0	688.3	674.4	2.87

Table C5. Moisture Corrections from 24-hr (1).

Mixture(s) : 18-hr (1)
Date : 7/7/2009

Pan #	Pan Wt. (g)	Pan & Sample Wt. (g)	OD-Pan & Sample Wt. (g)	Moisture Content (%)
1	158.8	660.3	651.1	1.87
2	118.0	616.0	606.4	1.97
3	150.8	650.5	643.1	1.50
4	200.9	701.6	694.1	1.52
5	177.1	678.1	671.5	1.33
6	-	-	-	-
7	293.2	790.6	785.0	1.14
8	189.9	691.9	684.8	1.43

Table C6. Moisture Corrections from 18-hr (1).

Mixture(s) : 72-hr (1)

Date : 7/10/2009

Pan #	Pan Wt. (g)	Pan & Sample Wt. (g)	OD-Pan & Sample Wt. (g)	Moisture Content (%)
1	158.8	658.4	650.3	1.65
2	118.0	616.3	607.6	1.78
3	150.8	648.2	641.3	1.41
4	201.0	698.3	693.8	0.91
5	177.2	676.3	668.4	1.61
6	-	-	-	-
7	293.3	792.2	783.2	1.84
8	190.0	688.4	680.9	1.53

Table C7. Moisture Corrections from 72-hr (1).

Mixture(s) : 48-hr (1)

Date : 7/17/2009

Pan #	Pan Wt. (g)	Pan & Sample Wt. (g)	OD-Pan & Sample Wt. (g)	Moisture Content (%)
1	158.9	658.4	641.5	3.50
2	118.2	619.7	602.2	3.62
3	151.0	649.2	632.8	3.40
4	201.1	701.6	684.9	3.45
5	177.3	677.1	660.2	3.50
6	281.8	782.9	766.1	3.47
7	293.3	793.1	775.7	3.61
8	-	-	-	-

Table C8. Moisture Corrections from 48-hr (1).

Mixture(s) : 48-hr (2)
Date : 7/20/2009

Pan #	Pan Wt. (g)	Pan & Sample Wt. (g)	OD-Pan & Sample Wt. (g)	Moisture Content (%)
1	159.0	657.5	642.0	3.21
2	118.2	615.5	599.3	3.37
3	151.0	649.3	634.3	3.10
4	201.1	702.3	686.0	3.36
5	177.3	677.8	662.7	3.11
6	281.7	782.5	766.4	3.32
7	293.4	793.3	777.3	3.31
8	-	-	-	-

Table C9. Moisture Corrections from 48-hr (2).

Mixture(s) : 18-hr (2)
Date : 7/22/2009

Pan #	Pan Wt. (g)	Pan & Sample Wt. (g)	OD-Pan & Sample Wt. (g)	Moisture Content (%)
1	159.0	660.7	643.7	3.51
2	118.2	615.9	600.2	3.26
3	150.9	650.2	637.2	2.67
4	201.0	698.9	682.9	3.32
5	177.3	675.2	660.6	3.02
6	281.7	780.2	764.2	3.32
7	293.5	793.0	778.2	3.05
8	-	-	-	-

Table C10. Moisture Corrections from 18-hr (2).

Mixture(s) : 72-hr (2)
Date : 7/24/2009

Pan #	**Pan Wt. (g)**	**Pan & Sample Wt. (g)**	**OD-Pan & Sample Wt. (g)**	**Moisture Content (%)**
1	159.0	662.9	652.2	2.17
2	118.2	618.3	600.9	3.60
3	151.0	650.1	637.7	2.55
4	201.0	698.7	682.5	3.36
5	177.3	676.0	665.0	2.26
6	281.6	780.9	768.3	2.59
7	293.4	792.0	778.2	2.85
8	-	-	-	-

Table C11. Moisture Corrections from 72-hr (2).

Mixture(s) : 30-hr (1)
Date : 7/28/2009

Pan #	**Pan Wt. (g)**	**Pan & Sample Wt. (g)**	**OD-Pan & Sample Wt. (g)**	**Moisture Content (%)**
1	158.9	660.5	646.0	2.98
2	118.2	617.4	603.8	2.80
3	151.0	649.3	636.6	2.62
4	201.0	700.2	687.4	2.63
5	177.3	677.2	667.1	2.06
6	281.5	781.3	767.8	2.78
7	293.3	792.3	778.2	2.91
8	-	-	-	-

Table C12. Moisture Corrections from 30-hr (1).

Mixture(s) : 64°F (1)
Date : 8/26/2009

Pan #	Pan Wt. (g)	Pan & Sample Wt. (g)	OD-Pan & Sample Wt. (g)	Moisture Content (%)
1	158.9	659.1	650.3	1.79
2	118.2	618.4	607.0	2.33
3	150.9	651.1	644.8	1.28
4	201.0	701.7	695.9	1.17
5	177.3	677.5	665.8	2.40
6	281.6	782.1	774.6	1.52
7	293.4	793.8	787.7	1.23
8	-	-	-	-

Table C13. Moisture Corrections from 64°F (1).

Mixture(s) : 64°F (2)
Date : 9/2/2009

Pan #	Pan Wt. (g)	Pan & Sample Wt. (g)	OD-Pan & Sample Wt. (g)	Moisture Content (%)
1	158.9	659.2	646.1	2.69
2	118.2	619.4	608.1	2.31
3	150.9	651.5	639.8	2.39
4	201.0	701.6	688.1	2.77
5	177.3	677.8	667.0	2.21
6	281.6	782.0	771.0	2.25
7	293.4	794.2	781.8	2.54
8	-	-	-	-

Table C14. Moisture Corrections from 64°F (2).

Mixture(s) : 90°F (1)

Date : 9/17/2009

Pan #	Pan Wt. (g)	Pan & Sample Wt. (g)	OD-Pan & Sample Wt. (g)	Moisture Content (%)
1	158.9	656.5	646.8	1.99
2	118.2	618.1	610.5	1.54
3	150.8	652.6	642.2	2.12
4	201.0	700.9	692.1	1.79
5	177.3	678.0	667.3	2.18
6	281.6	781.0	770.5	2.15
7	293.4	794.1	786.6	1.52
8	-	-	-	-

Table C15. Moisture Corrections from 90°F (1).

Mixture(s) : 90°F (2)

Date : 9/21/2009

Pan #	Pan Wt. (g)	Pan & Sample Wt. (g)	OD-Pan & Sample Wt. (g)	Moisture Content (%)
1	158.9	659.4	649.3	2.06
2	118.2	618.6	609.2	1.91
3	151.1	651.7	641.2	2.14
4	201.0	701.6	690.5	2.27
5	177.3	678.5	668.2	2.10
6	281.4	782.1	771.4	2.18
7	293.4	794.3	783.7	2.16
8	-	-	-	-

Table C16. Moisture Corrections from 90°F (2).

APPENDIX D

MORTAR CUBE COMPRESSIVE STRENGTHS FOR MODIFIED STSB

APPENDIX D
LIST OF TABLES

Mixture(s) : 24-HR (1)
Date : 7/1/2009

#	Average Surface Area (in²)	Load (lbs)	Compressive Strength (psi)
1	4.018	19,250	**4,789**
	4.022		
	4.020		
2	4.066	19,000	**4,674**
	4.064		
	4.065		
3	4.024	19,750	**4,915**
	4.012		
	4.018		
4	4.068	20,050	**4,930**
	4.066		
	4.067		
5	3.994	19,950	**4,995**
	3.994		
	3.994		
6	4.042	19,950	**4,933**
	4.046		
	4.044		
7	4.014	19,200	**4,791**
	4.002		
	4.008		
8	4.046	19,700	**4,868**
	4.048		
	4.047		
9	4.032	21,150	**5,247**
	4.030		
	4.031		
		Average	**4,905**

Table D1. Compressive Str. 24-hr (1)

Mixture(s) : 18-HR (1)
Date : 7/8/2009

#	Average Surface Area (in^2)	Load (lbs)	Compressive Strength (psi)
1	3.998	20,950	**5,234**
	4.008		
	4.003		
2	4.020	20,250	**5,050**
	4.000		
	4.010		
3	3.972	20,500	**5,162**
	3.972		
	3.972		
4	4.010	20,750	**5,175**
	4.010		
	4.010		
5	4.014	20,700	**5,156**
	4.016		
	4.015		
6	4.052	20,900	**5,162**
	4.046		
	4.049		
7	4.064	21,950	**5,393**
	4.076		
	4.070		
8	3.970	21,850	**5,501**
	3.974		
	3.972		
9	3.960	20,650	**5,207**
	3.972		
	3.966		
		Average	**5,227**

TableD 2. Compressive Str. 18-hr (1)

Mixture(s) : 72-HR (1)

Date : 7/13/2009

#	Average Surface Area (in²)	Load (lbs)	Compressive Strength (psi)
1	3.996	19,950	**4,998**
	3.988		
	3.992		
2	3.994	20,100	**5,044**
	3.976		
	3.985		
3	4.004	20,850	**5,209**
	4.002		
	4.003		
4	4.018	21,350	**5,283**
	4.064		
	4.041		
5	3.976	20,350	**5,126**
	3.964		
	3.970		
6	3.982	20,850	**5,246**
	3.968		
	3.975		
7	4.048	21,750	**5,373**
	4.048		
	4.048		
8	4.046	21,700	**5,389**
	4.008		
	4.027		
9	4.000	20,100	**5,028**
	3.996		
	3.998		
		Average	**5,188**

Table D3. Compressive Str. 72-hr (1)

Mixture(s) : 48-HR (1)

Date : 7/19/2009

#	Average Surface Area (in²)	Load (lbs)	Compressive Strength (psi)
1	4.060	16,400	**4,037**
	4.064		
	4.062		
2	4.020	17,550	**4,368**
	4.016		
	4.018		
3	4.014	17,250	**4,297**
	4.014		
	4.014		
4	4.016	17,850	**4,455**
	3.998		
	4.007		
5	4.004	17,750	**4,429**
	4.012		
	4.008		
6	4.012	17,000	**4,246**
	3.996		
	4.004		
7	3.964	17,450	**4,399**
	3.970		
	3.967		
8	3.980	17,200	**4,300**
	4.020		
	4.000		
9	3.984	17,250	**4,332**
	3.980		
	3.982		
		Average	**4,318**

Table D4. Compressive Str. 48-hr (1)

Mixture(s) : 48-HR (2)

Date : 7/22/2009

#	Average Surface Area (in²)	Load (lbs)	Compressive Strength (psi)
1	4.042	17,550	**4,352**
	4.024		
	4.033		
2	4.012	18,000	**4,459**
	4.062		
	4.037		
3	3.998	18,500	**4,640**
	3.976		
	3.987		
4	4.000	19,350	**4,857**
	3.968		
	3.984		
5	4.030	18,500	**4,587**
	4.036		
	4.033		
6	3.988	16,200	**4,090**
	3.934		
	3.961		
7	4.038	19,300	**4,785**
	4.028		
	4.033		
8	4.006	18,100	**4,526**
	3.992		
	3.999		
9	4.020	18,550	**4,608**
	4.032		
	4.026		
		Average	**4,637**

Table D5. Compressive Str. 48-hr (2)

Mixture(s) : 18-HR (2)
Date : 7/23/2009

#	Average Surface Area (in²)	Load (lbs)	Compressive Strength (psi)
1	4.101	19,450	**4,758**
	4.074		
	4.087		
2	4.060	17,950	**4,426**
	4.050		
	4.055		
3	4.000	19,300	**4,828**
	3.996		
	3.998		
4	4.032	18,800	**4,671**
	4.018		
	4.025		
5	4.046	19,450	**4,806**
	4.048		
	4.047		
6	3.986	18,700	**4,695**
	3.980		
	3.983		
7	3.996	19,600	**4,898**
	4.008		
	4.002		
8	3.986	19,650	**4,914**
	4.012		
	3.999		
9	4.050	20,700	**5,091**
	4.082		
	4.066		
		Average	**4,787**

Table D6. Compressive Str. 18-hr (2)

Mixture(s) : 72-HR (2)

Date : 7/27/2009

#	Average Surface Area (in²)	Load (lbs)	Compressive Strength (psi)
1	4.044	20,000	**4,946**
	4.044		
	4.044		
2	4.050	19,300	**4,735**
	4.102		
	4.076		
3	4.032	19,300	**4,776**
	4.050		
	4.041		
4	4.058	20,350	**5,030**
	4.034		
	4.046		
5	3.968	18,950	**4,734**
	4.038		
	4.003		
6	4.062	20,050	**4,928**
	4.074		
	4.068		
7	3.992	17,450	**4,386**
	3.966		
	3.979		
8	3.966	18,100	**4,581**
	3.936		
	3.951		
9	4.127	19,550	**4,784**
	4.046		
	4.086		
		Average	**4,767**

Table D7. Compressive Str. 72-hr (2)

Mixture(s) : 30-HR (1)
Date : 7/29/2009

#	Average Surface Area (in²)	Load (lbs)	Compressive Strength (psi)
1	3.986	18,000	**4,529**
	3.964		
	3.975		
2	4.066	18,750	**4,627**
	4.038		
	4.052		
3	4.048	19,200	**4,737**
	4.058		
	4.053		
4	4.048	19,600	**4,855**
	4.026		
	4.037		
5	4.014	18,400	**4,574**
	4.032		
	4.023		
6	4.002	18,450	**4,606**
	4.010		
	4.006		
7	4.008	17,900	**4,443**
	4.050		
	4.029		
8	4.028	18,300	**4,546**
	4.024		
	4.026		
9	4.042	19,400	**4,808**
	4.028		
	4.035		
		Average	**4,636**

Table D8. Compressive Str. 30-hr (1)

Mixture(s) : 64°F (1)
Date : 8/27/2009

#	Average Surface Area (in²)	Load (lbs)	Compressive Strength (psi)
1	3.958	17,800	**4,494**
	3.964		
	3.961		
2	4.024	19,750	**4,913**
	4.016		
	4.020		
3	4.020	19,300	**4,788**
	4.042		
	4.031		
4	3.996	18,200	**4,554**
	3.998		
	3.997		
5	3.996	20,550	**5,148**
	3.988		
	3.992		
6	3.982	19,050	**4,782**
	3.986		
	3.984		
7	3.950	19,950	**5,047**
	3.956		
	3.953		
8	3.966	19,100	**4,816**
	3.966		
	3.966		
9	3.956	20,200	**5,105**
	3.958		
	3.957		
		Average	**4,850**

Table D9. Compressive Str. 64°F (1).

Mixture(s) : 64°F (2)
Date : 9/3/2009

#	Average Surface Area (in²)	Load (lbs)	Compressive Strength (psi)
1	4.026	18,700	**4,637**
	4.040		
	4.033		
2	4.000	19,550	**4,879**
	4.014		
	4.007		
3	4.014	18,450	**4,602**
	4.004		
	4.009		
4	3.952	18,900	**4,767**
	3.978		
	3.965		
5	4.056	19,100	**4,719**
	4.038		
	4.047		
6	4.012	18,400	**4,596**
	3.996		
	4.004		
7	3.905	19,450	**4,945**
	3.962		
	3.933		
8	4.058	19,150	**4,721**
	4.054		
	4.056		
9	4.002	17,900	**4,473**
	4.002		
	4.002		
		Average	**4,704**

Table D10. Compressive Str. 64°F (2).

Mixture(s) : 90°F (1)
Date : 9/18/2009

#	Average Surface Area (in²)	Load (lbs)	Compressive Strength (psi)
1	4.002	22,350	**5,582**
	4.006		
	4.004		
2	4.074	24,550	**6,034**
	4.062		
	4.068		
3	4.070	24,300	**5,985**
	4.050		
	4.060		
4	4.013	23,800	**5,951**
	3.986		
	4.000		
5	4.034	23,950	**5,934**
	4.038		
	4.036		
6	3.980	22,500	**5,642**
	3.996		
	3.988		
7	3.992	23,000	**5,762**
	3.992		
	3.992		
8	4.056	24,350	**5,976**
	4.093		
	4.074		
9	4.050	24,200	**5,988**
	4.032		
	4.041		
		Average	**5,873**

Table D11. Compressive Str. 90°F (1).

Mixture(s) : 90°F (2)
Date : 9/22/2009

#	Average Surface Area (in²)	Load (lbs)	Compressive Strength (psi)
1	4.044	19,650	**4,863**
	4.038		
	4.041		
2	4.048	19,350	**4,767**
	4.070		
	4.059		
3	3.975	19,050	**4,800**
	3.962		
	3.969		
4	4.024	18,600	**4,628**
	4.014		
	4.019		
5	4.024	18,750	**4,654**
	4.034		
	4.029		
6	4.026	19,100	**4,749**
	4.018		
	4.022		
7	4.127	19,050	**4,624**
	4.113		
	4.120		
8	3.956	17,700	**4,469**
	3.966		
	3.961		
9	4.098	18,950	**4,635**
	4.078		
	4.088		
		Average	**4,688**

Table D12. Compressive Str. 90°F (2).

APPENDIX E

SAND PROPERTIES

APPENDIX E
LIST OF TABLES

Table Page

Fine Agg. Properties: ASTM C 128, C 702, and C 566

Sample Number :	#1
Pan Wt. (g) :	631.3
Pan & Sample Wt. (g) :	1411.9
OD-Pan & Sample Wt. (g) :	1388.7
OD-Sample Wt. (g) :	757.4
Moisture Content (%) :	3.063

Date : 5/29/2009

Sieve Number	Empty Sieve Wt. (g)	Sieve and Sample Wt. (g)	Sand Wt. (g)	% Passing	% Retained	Cummulative % Retained
#4	470.2	475.9	5.7	99.25	0.75	0.75
#8	432.6	467.3	34.7	94.67	4.58	5.33
#16	402.3	510.3	108.0	80.42	14.25	19.58
#30	367.0	587.0	220.0	51.39	29.03	48.61
#50	337.6	587.6	250.0	18.40	32.99	81.60
#100	316.6	438.9	122.3	2.26	16.14	97.74
Pan	330.8	347.9	17.1	-	2.26	-

TOTAL : 757.8

% Loss/Gain : 0.05%

F.M. : 2.54

Table E1. Sieve Analysis Sample #1

Fine Agg. Properties: ASTM C 128, C 702, and C 566

Sample Number :	#2
Pan Wt. (g) :	635.5
Pan & Sample Wt. (g) :	1523.4
OD-Pan & Sample Wt. (g) :	1494.6
OD-Sample Wt. (g) :	859.1
Moisture Content (%) :	3.352

Date : 5/29/2009

Sieve Number	**Empty Sieve Wt. (g)**	**Sieve and Sample Wt. (g)**	**Sand Wt. (g)**	**% Passing**	**% Retained**	**Cummulative % Retained**
#4	470.1	476.6	6.5	99.25	0.75	0.75
#8	432.7	471.0	38.3	94.67	4.58	5.33
#16	402.2	524.8	122.6	80.42	14.25	19.58
#30	367.0	613.3	246.3	51.39	29.03	48.61
#50	337.5	622.5	285.0	18.40	32.99	81.60
#100	316.5	456.7	140.2	2.26	16.14	97.74
Pan	330.7	350.8	20.1	-	2.26	-

TOTAL : 859.0

% Loss/Gain : 0.00%

F.M. : 2.53

Table E2. Sieve Analysis Sample #2

VITA

Clarence Doug Yarholar

Candidate for the Degree of

Master of Science

Thesis: EFFECTS OF CURING TIME AND CURING TEMPERATURE ON THE STANDARD TEST FOR STRAND BOND

Major Field: Civil Engineering

Biographical:

Personal Information: Born in Oklahoma City, Oklahoma, on May 19, 1984, the son of Doug and Vickie Yarholar.

Education: Graduated from Edmond Santa Fe High School, Edmond, Oklahoma, in May 2002; received a Bachelor of Science in Civil Engineering from Oklahoma State University, Stillwater, Oklahoma in December 2008. Completed the requirements for the Master of Science in Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2010.

Experience: Raised in Edmond, Oklahoma; employed as an Engineer Intern by Oklahoma Department of Transportation, Oklahoma City, Oklahoma and Edmond, Oklahoma, in the summers of 2006 and 2007, respectively, employed as a Project Manager’s Assistant by Duit Construction, Edmond, Oklahoma, in the summer of 2008; employed as a Research and Teacher’s Assistant by Oklahoma State University Department of Civil Engineering, Stillwater, Oklahoma, 2008 – 2009.

Name: C. Doug Yarholar Date of Degree: May, 2010

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: EFFECTS OF CURING TIME AND CURING TEMPERATURE ON THE STANDARD TEST FOR STRAND BOND

Pages in Study: 121 Candidate for the Degree of Master of Science

Major Field: Civil Engineering

Scope and Method of Study: The purpose of this study was to observe and determine the effects of the curing environment on the STSB method. Through multiple rounds of NASP funded research, the STSB has proven to be a valid test method for assessing performance of prestressing strand bond with concrete and to correlate bond performance to transfer lengths and development lengths in prestressed members. The study focused on altering the curing time and temperature, while maintaining the required mortar strength as specified by the STSB method. Curing conditions lacking in environmental control will affect concrete strength and maturity. In attempting to maintain simplicity of the STSB procedures, the results of this study are potentially valuable to strand producers and prestressed plant operators.

Findings and Conclusions: The results from the modified STSB test program demonstrated that curing conditions must adhere to the requirements of the STSB procedures to ensure valid pull-out force results. The pull-out forces increase as the w/c ratio of the mixture (decreased curing time) decreases for mixtures of the same mortar strength. In addition, the pull-out values increase as the curing temperature increases for mixtures of the same mortar strength. Interestingly, the STSB method illustrated extreme sensitivity for mixtures with w/c ratios of less than 0.50, and pull-out forces appeared to approach a minimum value, or become less sensitive, as the w/c ratio increased, if the data were extrapolated. The increase in pull-out forces potentially describes a change in behavior in the bond strength between the prestressing strand and mortar at approximately a w/c ratio of 0.50.

ADVISER'S APPROVAL: Dr. Bruce W. Russell