UN-TENSIONED PULLOUT TESTS TO PREDICT THE BOND QUALITY OF DIFFERENT PRESTRESSING REINFORCEMENTS USED IN CONCRETE RAILROAD TIES

by

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Abstract

An experimental testing program was conducted at Kansas State University (KSU) to test the bond characteristics of various 5.32-mm-diameter steel wires and smaller diameter (less than 0.5 in.) strands used in prestressed concrete railroad ties. A total of 13 wires and six strands produced by seven different steel manufacturers were used during this testing.

Since no wire bond pullout test currently exists, one was developed and its validity tested. This un-tensioned pullout test could serve as a quality control test similar to the standard test for strand bond (ASTM A1081) that has been developed for pretensioned strands. This strand test is currently not verified for strands less than 0.5-in. in diameter, so the procedure was also scrutinized using strands common in the concrete railroad tie industry.

Some of the wires and strands contained surface indentations. It is generally accepted that indentations in the reinforcements improve the bond between the steel and concrete. To further complicate the issue, reinforcements with different surface conditions (rust, oils, lubricants) are allowed to be used in the concrete ties which further affects the bond quality of the reinforcements.

However, no standardized indentation patterns (shape, size, depth of indent, etc.) or surface conditions (degree of rusting, amount of surface lubricants, etc.) are utilized by all wire and strand manufacturers. Thus, the corresponding bond behavior of these different reinforcements when placed in various concrete mixtures, in terms of average transfer lengths and typical variations, is essentially unknown.

The purpose of this testing program was to develop (in the case of wires) or verify/develop (in the case of strands) a pullout testing procedure predictive of the reinforcement's bond performance in a prestressed application. The test should be relatively inexpensive, demonstrably repeatable, and easily reproducible. Results from the un-tensioned pullout tests were compared to transfer length measurements from accompanying pretensioned concrete prisms in the lab.

Additionally, pullout tests and transfer length measurements were obtained at an actual concrete railroad tie manufacturing plant. The obtained data was compared to the lab data and analyzed to further understand the relationship between un-tensioned pullout tests and pretensioned concrete members.

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Chapter 1 - Introduction

1.1 Background

Use of prestressed concrete railroad ties is increasing in the United States as the railroad industry continues to become more efficient. These concrete ties are intended to be more durable, environmentally friendly, and longer lasting than their wooden railroad tie counterparts. However, many of these concrete ties are cracking long before their intended life spans have been met. In some cases, cracking has been primarily linked to the bond performance of the wires and strands used to reinforce the concrete ties.

In order for these prestressed concrete ties to function adequately over their expected service life, prestressing force from the steel must be fully introduced into the concrete before the rail load is applied at the rail seat. In general, the rail seat is located 21 inches from the end of the tie. This means the Transfer Length – the length required to transfer the prestressing force into the concrete member – must be less than 21 inches. If this does not occur, the concrete railroad tie will not have the full design capacity at the time of load application and may also be in danger of cracking (material failure). To ensure the prestressing force is transferred fully to the concrete, it is crucial to have a good contact surface ("good bond") between the prestressing reinforcement and the surrounding concrete.

In the case of concrete railroad ties, indented 5.32-mm-diameter, low-relaxation steel wires have become the industry norm. However, some manufacturers use 3/8-in.-diameter, low-relaxation steel strands. Still others are interested in 5/16-in.-diameter low-relaxation steel strands from a cost standpoint. These smaller diameter strands (less than 0.5 in. diameter) can also be indented similar to the 5.32-mm-diameter wires.

It is generally accepted that indentations in the reinforcements improve the bond between the steel and concrete. However, currently no standardized indentation pattern (shape, size, depth of indent, etc.) is utilized by all wire and strand manufacturers. Thus, the corresponding bond behavior of these different reinforcements when placed in various concrete mixtures, in terms of average transfer lengths and typical variations, is essentially unknown.

The industry is eager to understand more about the issue of bond. This knowledge can be gained by developing a reliable, repeatable, and reproducible quality control bond test to determine the bond quality amongst various prestressing wires and strands. Such a quality control bond test would allow the industry to 1) be reasonably sure from lab testing how various reinforcements will perform and 2) report the relative bond performance of various reinforcements. If a problem is noted in the lab, corrective measures can be taken before concrete ties are mass produced in manufacturing plants. This concept can be simplified by stating it in a relatively general manner: good bond in the lab is indicative of good bond in the field.

It’s not enough though to know the relative bond quality of the reinforcements. The real importance of a good quality control bond test is that it can potentially predict the transfer length of concrete railroad ties with good precision and relative accuracy.

Currently, a pullout test exists for 0.5-in.-diameter and larger strands (Ramirez and Russell, 2008), but no standard tests exist to quantify the bond performance of these reinforcement types used by the concrete railroad tie industry. Thus, there exists a need to develop a standardized test to accurately quantify a wire’s bond-ability with reasonable assurance.

This report presents results of an experimental testing program performed at Kansas State University (KSU) where such a bond test was developed for prestressing wires and the strand test was expanded (modified) for smaller diameter strands. The developed wire test and expanded strand test were verified by correlating the data to measured transfer lengths from pretensioned concrete prisms. Additionally, the findings at KSU were expanded and used at an actual concrete railroad manufacturer to see how well the developed tests would correlate to transfer lengths of actual, full-sized concrete railroad ties.

1.2 Objectives

The purpose of the entire testing program was to develop (in the case of wires) or verify/develop (in the case of strands) a pullout testing procedure predictive of the reinforcement’s bond performance in a prestressed application. The test should be relatively inexpensive, demonstrably repeatable, and easily reproducible.

Of great importance was investigating what portion of a reinforcement’s bond performance can be attributed to the indent geometry and what portion can be attributed to the surface condition. Researchers expected the wires and strands to be affected to different degrees by these two effects (indent geometry and surface condition), which were investigated by testing the reinforcements in both their “as-received” and “cleaned” conditions. The “as-received” specimens provided a baseline reading for expected bond performance as the reinforcements were received from their respective suppliers. The “cleaned” specimen tests were performed on bare steel by removing rust, oils, and surface lubricants with an acidic solution. This process allowed researchers to better separate out the bond attributed to surface condition from the bond attributed to indent geometry.

1.2.1 Lab Phase; Wire and Strand Pullout Testing in Mortar

Pullout testing in the lab focused on developing a quality control pullout test for 5.32-mm-diameter prestressing wires and for smaller diameter prestress strands. The two primary research variables for the testing portion of the lab phase were indent geometry and surface condition. This is of great importance because it allows the researchers to better distinguish what portion of a reinforcement’s bond performance can be attributed to the indent geometry and what portion can be attributed to the surface condition. These two effects were investigated by testing the reinforcements in both their “as-received” and “cleaned” conditions.

First, indentation geometry of the steel prestressing reinforcements was investigated by testing them in their “as-received” surface conditions. This allowed for the relative bond performance of the reinforcements to be examined and a baseline for expected bond performance to be established.

Second, surface condition of the reinforcements was tested by cleaning them. This occurred by performing further pullout testing on some of the reinforcements after they had been subjected to the cleaning process described in depth in Section 3.3. “Cleaned” specimen tests were performed on bare steel by removing rust, oils, and surface lubricants with an acidic solution.

Results of these “cleaned” specimens were compared to the “as-received” specimens. This process allowed the researchers to better separate out the bond attributed to surface condition from the bond attributed to indent geometry.

The testing matrix for the pullout tests performed in the lab can be seen in Table 1.1. Each reinforcement was tested six times, and the results averaged, to give the expected bond performance of each. Both “as-received” and “cleaned” pullout results were compared to the measured transfer length of accompanying pre-tensioned prisms.

In the case of the wire pullout test, bond performance models generated by the “as-received” and “cleaned” pullout tests and accompanying pre-tensioned prisms were scrutinized using an additional, thirteenth wire WM, from a seventh different steel manufacturer. This wire was not part of the test development phase. It was used to verify the testing procedure and determine how good the model was at predicting bond performance.

A third parameter was looked at for strand testing: bond length. This was significant for the smaller diameter strands (less than 0.5 in.) as they were not able to handle as much load before rupturing due to decreased surface area and cross-sectional area compared with larger diameter strands (0.5 in. and larger). This testing program sought first to verify if a 16-in. bond length used for the Standard Test for Strand Bond (Ramirez and Russell, 2008) would be adequate for smaller diameter strands. If the 16-in. bond length was determined to be inadequate (too long), then a modified version of the standard strand bond test would be proposed for smaller diameter strands. Preferably, all parameters except bond length would remain the same as the standard strand bond test.

Table 1.1 Testing matrix of lab phase

				Number of test specimens		
	Reinforcement Manufacturer	Reinforcement Identification	Indentation Type	Transfer lengths (no. of ends)	As-received un-tensioned pullouts	Cleaned un-tensioned pullouts
Wires	A	[WA]	Smooth	6	6	6
	A	[WB]	Chevron	6	6	
	A	[WC]	Spiral	6	6	
	B	[WD]	Chevron	6	6	
	B	[WE]	Spiral	6	6	6
	B	[WF]	Diamond	6	6	6
	C	[WG]	Chevron	6	6	6
	D	[WH]	Chevron	6	6	6
	E	[WI]	Chevron	6	6	
	E	[WJ]	Chevron	6	6	
	F	[WK]	4-Dot	6	6	6
	F	[WL]	2-Dot	6	6	
	G	[WM]	Chevron	6	6	6
	Wires Total:			**78**	**78**	**42**
Strands	A	[SA]	3/8" 7-Wire, Smooth	6	12	6
	A	[SB]	3/8" 7-Wire, Indented	6	12	6
	A	[SC]	5/16" 3-Wire, Smooth	6	12	6
	B	[SD]	3/8" 7-Wire, Indented	6	12	6
	C	[SE]	3/8" 7-Wire, Indented	6	12	6
	D	[SF]	3/8" 3-Wire, Indented	6	12	6
	Strands Total:			**36**	**72**	**36**

Note: (6) of the "as-received" strand specimens were tested both at a 16 in. bond length and a 9 in. bond length.

1.2.2 Plant Phase; Wire and Strand Pullout Testing in Concrete

The plant portion of the wire and strand bond pullout tests, performed in concrete, included un-tensioned pullout tests. The plant phase refers to the research team from Kansas State University (KSU) going to CXT Concrete Ties (CXT) in Tucson, Ariz. to measure transfer lengths in actual, non-prismatic concrete railroad ties. Pullout specimens were cast to accompany transfer lengths taken from the railroad ties. Fifteen reinforcements from seven different steel manufacturers were used in the plant phase and were the same as the reinforcements used for pullout and transfer length tests at KSU. Approximately fifty transfer length measurements and six pullout specimens were obtained for each reinforcement type.

This goal of this plant phase was to determine how well pullout tests developed in the lab could correlate to transfer lengths of actual, full-sized concrete railroad ties. The testing matrix for the pullout tests performed in the plant can be seen in Table 1.2.

Table 1.2 Testing matrix of plant phase

	Reinforcement Manufacturer	Reinforcement Identification	Indentation Type	Number of test specimens	
				Transfer lengths (no. of ends)	As-received un-tensioned pullouts
Wires	A	[WA]	Smooth	49	4
	A	[WB]	Chevron	50	5
	A	[WC]	Spiral	47	4
	B	[WD]	Chevron	49	6
	B	[WE]	Spiral	48	6
	B	[WF]	Diamond	49	6
	C	[WG]	Chevron	49	6
	D	[WH]	Chevron	50	6
	E	[WI]	Chevron	50	6
	E	[WJ]	Chevron	47	6
	F	[WK]	4-Dot		
	F	[WL]	2-Dot	47	6
	G	[WM]	Chevron	49	6
	Wires Total:			**584**	**67**
Strands	A	[SA]	3/8" 7-Wire, Smooth	45	6
	A	[SB]	3/8" 7-Wire, Indented	50	6
	A	[SC]	5/16" 3-Wire, Smooth	48	4
	Strands Total:			**143**	**16**

1.3 Scope

Chapter 2 reviews the research found to be most informative and helpful when developing quality control pullout tests for steel prestressing wires and smaller diameter steel prestressing strands.

Chapter 3 covers the preliminary setup involved in the pullout testing at KSU. This includes reinforcements, reinforcement storage, cleaning procedure, and machinery used to perform the pullout testing.

Chapter 4 discusses development, testing, results, and analysis of the wire pullout tests performed at KSU.

Chapter 5 discusses testing, results, and analysis of the strand pullout tests performed at KSU.

Chapter 6 reviews experimental pullout testing in concrete performed at an actual concrete railroad tie plant. This includes testing, results, and analysis of these tests.

Chapter 7 compares results of pullout tests performed in the lab (Chapters 4 and 5) to pullout tests performed in the plant (Chapter 6).

Chapter 8 summarizes the conclusions and gives recommendations developed from this research project.

Chapter 2 - Literature Review

This chapter discusses the research found to be most informative and helpful when developing quality control pullout tests for steel prestressing wires and smaller diameter steel prestressing strands. The first major section discusses the research used to develop a pullout test for 0.5-in.-diameter strands. The second major section is devoted to research focused on the modeling of and testing done on 5.32-mm-diameter wires and smaller diameter strands.

2.1 0.5-in.-Diameter and Larger Strand Bond Testing

2.1.1 Introduction

The original transfer length equations given in ACI and AASHTO design requirements were designed in the late 1950s and early 1960s using Grade 250 stress-relieved strand (Ramirez and Russell, 2008). Since then, Grade 270 low-relaxation strand has been engineered and is now the most widely used for prestressing applications. A study performed by Cousins, Johnston and Zia (1990) in the mid-1980s showed many actual transfer lengths were larger than predictions using the code equations (Ramirez and Russell, 2008).

Since then, numerous research projects have investigated various performance parameters of prestressing strand in an attempt to better understand the factors that affect a strand's transfer length. All of these performance parameters were investigated to develop a standardized test that would, in the end, be able to neatly categorize the strand based on one parameter – its "bond-ability." "Bond-ability" is the all-encompassing term for how well or how poorly a prestressing strand bonds to either the concrete or mortar it is encased in. Three such standardized tests have been developed as follows:

1. The Moustafa Test, or Large Block Pullout Test, was first introduced in 1992 and pulls untensioned strands from large concrete blocks (Logan, 1997; Ross and Russell, 1997; Ramirez and Russell, 2008).
2. The PTI Bond Test was developed primarily for 0.6-in. strand in 1994 (Ramirez and Russell, 2008). This test was the inspiration for the original NASP Bond Test and pulls untensioned strands from a neat cement mortar, or mortar made with no sand and only cements (Ramirez and Russell, 2008).

3. The current NASP Bond Test – known more formally as the Standard Test Method for the Bond of Prestressing Strand – pulls untensioned strands from a sand-cement mortar (Russell, 2006; Ramirez and Russell, 2008). This test subsequently became an ASTM standard (ASTM A1081) in 2012.

The goal of these three proposed pullout tests is to provide an acceptance criterion that quantifies the "bond-ability" of various strands from different strand manufacturers. Based on work done by Russell and Paulsgrove (1999b) for the North American Strand Producers (NASP), "the NASP Bond Test has proven to be the most reliable test of the three" (Ramirez and Russell, 2008). The work that led to the development of this reliable strand bond pullout test is presented below.

2.1.2 History of Strand Bond Testing Since the Mid-1990s

2.1.2.1 Abrishami and Mitchell (1996)

Abrishami and Mitchell (1996) developed analytical expressions based on responses obtained from experimental results of bond stress vs. end slip measurements. The researchers looked at both "pullout" and "push-in" testing. Their primary goal was to develop analytical equations that would predict the bond performance of a pullout specimen. They used finite elements to determine a governing differential equation to quantify the bond stress as a function of the slip which, in turn, is a function of the distance along the reinforcement.

For the case of a pullout specimen, a tensile force was applied at the bottom of the reinforcement specimen. The boundary conditions were known from this information since the strain in the concrete and the steel must be equal to zero at the top face of the specimen. Similarly, the strain of the concrete and steel at the bottom face were known based on the principles of axial deformation. From this information and the governing differential equation that relates bond stress, slip, and axial distance, the constants of integration were found and the top slip and bottom slip were quantified as a function of known parameters (length, Young's moduli, cross-sectional areas, and applied pullout force). The average slip was produced as the average of the top and bottom slip and was used to predict the pullout force required to cause a certain amount of slip (not used as an input to predict). The same analysis was done for the case of a push-in specimen using the new boundary conditions, and the derived expressions were identical as was expected. This methodology was used a third time (again changing the boundary conditions to appropriate values) for the case of a combination pullout/push-in specimen. For the linear range, the derived expression again was identical to other two cases.

Eight specimens were tested either by pullout testing or by combined pullout/push-in specimens to compare to the analytical predictions. The specimens varied in size from 150 mm long at the shortest, up to 300 mm long at the longest. Half of the specimens were tested using a technique developed by Abrishami and Mitchell (1992) in which a “strain control” loading rate was used. The other half were tested as “standard pullout specimens.” The shorter specimens showed a more uniform bond stress and the longer specimens showed higher stress concentrations at the loaded end(s). The authors also concluded the specimens failing in splitting showed an almost uniform bond stress distribution after the crack formed. The combined (pushing and pulling) loading gave the closest to uniform bond stresses at about a 1.10 ratio of maximum to average bond stress. The specimens failing in pullout had a ratio of 1.37 and the specimens failing in splitting had a ratio of 1.26. The authors did not conclude how accurately the derived equations predicted the pullout force required for a given end slip based on the experimental results.

2.12.2 Logan (1997)

Logan (1997) investigated the Moustafa pullout test method and its ability to accurately predict the transfer length of a pretensioned concrete member. The strand bond tests Logan performed were conducted using 0.5-in. strand from six different North American strand producers. Logan’s tests were a direct response to earlier research conducted in the 1980s and early 1990s that indicated large variances in strand bond quality among the different strand producers. Due to the lack of any ASTM standards concerning bond performance, Logan implemented a test program that included pullout tests, end slip measurements at prestress release and 21 days, and transfer length tests. The pullout test portion was based on the Moustafa method and consisted of a group of six, 34-in.-long, saw-cut strand specimens from each of the six manufacturers. The 36 strand specimens (six groups of six specimens) were cast vertically into the concrete with an 18-in. bond length and a 2-in. bond breaker at the top. Both pullout test blocks, as well as the transfer length beams (described later), were cast the same day with the same mix design. All of the concrete specimens were heat-cured overnight to an average compressive strength of 4,350 psi for the pullout large blocks and 4,254 psi for the transfer length beams.

Pullout tests took place the morning after casting and results were recorded by Don Logan and Bruce Russell. These were conducted with a single-strand jack loaded at a rate of 20 kips per minute and were not stopped until the strands had been completely pulled out or the loading rate could no longer be maintained. Four of the six strand groups averaged a maximum pullout force above 36 kips. The remaining two groups averaged less than 12 kips of maximum pullout force and withdrew substantially before reaching these forces. Specimens used for end slip measurements and transfer length testing were rectangles with a 6.5-in. x 12-in. cross-section. Each beam had a single pretensioned, 0.5-in.-diameter, low-relaxation Grade 270 strand embedded 2-in. from the bottom face of the beam. The formwork was built such that the beams were poured side by side, with each of the six cavities housing one of the six strands being tested. The beams were poured continuously in 90-ft-long sections and then saw-cut into five shorter beams 18-ft-long each. End slip measurements were taken directly after de-tensioning, which occurred by flame-cutting and saw-cutting the ends of the beams as is typical in prestressing plants.

These end slip measurements were used to calculate the transfer length of the means and were compared to the predicted ACI transfer length of 29 in. Four of the strand types averaged an initial transfer length of 15 in. The two poor bonding strands averaged transfer lengths of 24 in. and 34 in., respectively. The 21-day end slip measurements showed transfer lengths of the two poor bonding specimens increased significantly. The transfer length of Group 5 increased 16 in. (to 40 in.) and the transfer length of Group 6 increased 14 in. (to 48 in.). Logan concluded the Moustafa pullout test was a reasonably good predictor of transfer length and, therefore, of bond characteristics for 0.5-in. strand. In short, he concluded that a higher pullout force correlates directly to a shorter transfer length. Logan also concluded that end slip measurements taken immediately after de-tensioning may not accurately detect poor bond characteristics of prestressing strand.

2.1.2.3 Rose and Russell (1997)

Rose and Russell (1997) performed both un-tensioned and tensioned pullout tests with the intent of correlating these results to measured transfer lengths of prestressed concrete beams. The authors theorized the surface condition of the strand plays a large role in the strand's "bond-ability." Most notably, the strand can become contaminated by either rust or surface lubricants. Due to the relatively inexpensive cost of an un-tensioned pullout test compared to a direct transfer length measurement, a direct correlation between the two values would allow the pullout test to serve as a good indicator of prestressing strand performance inside a beam. Tests were performed on three different 0.5-in., low-relaxation, Grade 270 strand samples from three different strand manufacturers – A, B, and C. Strands A, B and C were all tested in their as received conditions (A). Additionally, strand C was tested three additional times by modifying its surface condition in the following ways: cleaning (C) the strand using muriatic acid, washing with water, and letting it dry; cleaning as before and then lubricating the strand with a silane (S) spray; and cleaning the strand as before and then letting it sit in a damp environment for three days to promote weathering (W) of the strand. In total, this led to six different casting and testing cycles. Each cycle consisted of three pretensioned beams, a large block containing 12 un-tensioned pullout specimens, and two tensioned pullout tests. All specimens for each cycle were poured from the same batch of concrete to ensure minimal variation.

The un-tensioned pullout tests consisted of 6-ft-long strands being cast vertically into the large pullout block with an embedment length of 18 in., and bond breakers at both the dead and live ends of the pullout block. The target release strength was set to be 4,000 psi. All of these parameters were used to imitate the work done by Moustafa and Logan using large-block pullout tests. The applied force, dead end slip, and live end slip were measured for each pullout strand during time of testing. The beams used to collect transfer length data were each 17 ft in length with a cross section of 6 in. x 12 in. The beams containing silane-treated strands were fabricated at 24 ft instead of 17 ft to accommodate the longer anticipated transfer lengths. Each beam contained two strands cast 2 in. from the bottom face of the beam's surface. Each beam was allowed to cure for 48 hours in the formwork and under plastic to retain heat and moisture. A DEMEC mechanical strain gage was used to measure surface strain on both sides of the beam at the location of the strand. Surface strain was measured before and after de-tensioning. End slip measurements were also taken on these beams using calipers.

Results of the un-tensioned pullout specimens followed a logical trend. As expected, rust on the weathered strand C (CW) increased the force required to pull the strand from the concrete. Similarly, strand C samples with silane lubricant (CS) sprayed on them required less force to be pulled from the concrete. Both of these measurements were taken relative to the as-received strand C (CA) specimens. In general, the un-tensioned pullout specimens were consistent relative to the other strands in their groups, leading the researchers to have faith in the results. Results regarding the beams used for transfer length and end slip measurements were consistent with the trend of the pullout results, with ends adjacent to flame-cutting showing much longer transfer lengths than other locations. The authors concluded that the un-tensioned pullout test was not a good indicator of pretensioned bond, based primarily on results of the silane-lubricated specimens and the ends that had been flame-cut. Second, the authors concluded even when silane specimens are omitted, there were still no “clear or useful relationships between pullout strength and transfer length.” Third, the researchers found the surface condition does indeed affect bond performance of strand. A rough surface positively affects bond and a lubricated surface negatively affects bond. Finally, the researchers concluded the un-tensioned pullout test must include a standardized load rate, geometry, and concrete mix to make results of the test relevant and useful for determining pretensioned bond.

2.1.2.4 Russell and Paulsgrove (1999a)

Russell and Paulsgrove (1999a) examined three pullout tests that were, at the time, being proposed as quality control tests for strand bond. The three tests compared for repeatability were the Moustafa pullout test in concrete, the PTI pullout test in grout, and the friction bond pullout test that uses neither concrete or grout, but rather a mechanical butt splice and two lengths of the strand being tested. The goal of the testing program was to either accept one of the test methods as a repeatable test, or to develop a new test that is both accurate and more repeatable and reproducible than any current bond performance tests. Nine new strands were tested in their as received condition and were obtained from various strand manufacturers. Two additional strands were tested as control strands because their bond performance was already known from Logan (1997). Four testing sites were used: one research laboratory, one materials testing laboratory, and two testing sites located at the strand manufacturer sites. All 11 strand samples were 0.5-in., Grade 270 low-relaxation strand. All were kept confidential in such a way that all testing was done as a “blind study” to everyone except the P.I. (Bruce Russell). Each set of tests consisted of six strand samples. Since there were two testing sites for the Moustafa test, the compressive strength of the concrete varied. At the strand manufacturer’s site, the concrete’s compressive strength for the first set of tests was unknown, but was 3700 psi for the second set of tests. The concrete’s compressive strength was 5000 psi at the materials testing laboratory. The compressive strength of the grout for the PTI pullout test ranged between 3700-4000 psi for the six separate batches.

The test procedure for the Moustafa test is documented by Logan (1997). The test procedure for the PTI pullout test was developed by the Post-Tensioned Institute (PTI) for 0.6-in. strand using grout. The test allows specimens to be tested in a strength range of 3500-4000 psi, with the strength determined using 2-in. cubes. The load is applied by a mechanical jack at a rate of 0.10 in./minute. The specimen passes the test if at least 8000 lbf of force is required to cause a dead end slip of 0.01 in. The dead end slip is measured using an LVDT. The friction bond pullout test procedure consists of two identical strands connected with a crimped butt splice in the middle. Maximum strand tension force is recorded as the connection fails. An actuator pulled the strand from the top using standard 0.5-in. strand chucks to grip the specimens.

Results of the Moustafa pullout tests show the general trend of the strands’ bond performance is indicated by the Moustafa method. This general trend accurately ranks the relative bond capacity of each strand at each different testing location. However, the Moustafa test showed inconsistencies at the different testing locations. At the materials testing laboratory, the entire set of results were nearly 15% larger than those reported by the strand manufacturer. This “unstable variation” led the author to conclude the test is unstable and, therefore, inconclusive as a repeatable quality control test, because the Moustafa test would “inconsistently reject and accept strands depending on test site.” The author further concluded that unidentified variables need to be tightened up for a bond quality control test. Both the Moustafa and PTI pullout tests were able to rank relative strand bond performance. The friction pullout test was not able to do the same, inadequately distinguishing strand bond performance. The author’s overall recommendation was to further refine the current Moustafa and PTI pullout tests by eliminating inconsistencies in testing variables. This recommendation became the basis for the “NASP Round Two” set of tests the author continued with after completion of the testing regiment explained here.

2.1.2.5 Russell and Paulsgrove (1999b)

Russell and Paulsgrove (1999b) looked further at the repeatability and reproducibility of Moustafa, PTI, and NASP pullout tests based on the recommendation and findings of Russell and Paulsgrove (1999a). The Moustafa and PTI pullout tests follow the procedures documented in Logan (1997) and Russell and Paulsgrove (1999a), respectively. The NASP pullout test is a new test developed by the author of this paper and is based heavily on the PTI pullout test with two major modifications. First, a sand-cement mortar is used instead of the neat mortar (grout) used in the PTI pullout test. Second, the pullout force is recorded at a free end slip of 0.01 in, 0.10 in., and at its maximum value. In the PTI test, the pullout force is reported only at the 0.01-in. value for end slip at the free end of the specimen. The loading rate (0.10 in./minute), diameter of the steel can (5 in.), bonded embedment length (16 in.), and bond breaker length (2 in.) all remained the same from the PTI test to the NASP test. Both the PTI and NASP pullout tests were performed at two locations: Florida Wire and Cable (FWC) and the University of Oklahoma (OU). Additionally, the Moustafa pullout test was performed at Stresscon Corp. (SC). For the NASP test, both FWC and OU performed two rounds of testing for each set of strand specimens. Only one round of the Moustafa and PTI tests were performed at each location. For consistency, six specimens represented one round of testing per strand type for each testing procedure.

All nine strand types used in this study were 0.5-in.-diameter, Grade 270, low-relaxation strand and were tested in their as-received condition. The Moustafa tests began when the concrete reached a compressive strength of 4000 psi. With the PTI tests and NASP tests, Series One began when the mortar reached a compressive strength of 3500 psi based on the 2-in. mortar cube strengths. Series Two tests for both OU and FWC did not begin until the mortar strength was higher at both testing sites. For FWC, Series Two tests took place for mortar cube strengths between 3560-4760 psi. For OU, Series Two tests took place for mortar cube strengths between 4470-5610 psi. A concrete mix containing Type III cement and admixtures was used for all Moustafa tests. A neat cement mortar mix containing Type I cement was used for all PTI test specimens. A sand-cement mortar mix containing Type III cement was used for all NASP specimens, except for the FWC Series One NASP tests.

Moustafa test results from all three testing sites gave the same result as the NASP Round One Moustafa test results: the Moustafa test is not able to be consistently reproduced at different testing facilities. Yet, results of the Moustafa tests were again consistent at indicating relative strand performance amongst the strands being testing at each individual testing facility. Results from OU and Stresscon were consistent albeit not “perfect,” but results from FWC were consistently much lower than the other two locations. When the values for all nine strand groups were averaged, FWC results were 8000 lbf lower than OU and Stresscon results. In the author’s mind, these large testing variations made all other discussion irrelevant. “Statistical comparisons are moot until the causes of large differences between the test sites is [sic] resolved.”

PTI test results showed good correlation between testing sites for both maximum pullout force and pullout forces measured at 0.10 in. The R^2 for the maximum, 0.10-in., and 0.01-in. end slip measurements came out to be 0.87, 0.90, and 0.73, respectively. This shows the 0.01-in. measurements had the least correlation between sites "indicating significantly weaker ability to reproduce results between test sites."

The NASP test showed very similar results for the maximum, 0.10- in., and 0.01-in. end slip pullout values, leading to two very important conclusions. First, the NASP test showed excellent repeatability at each testing site from Series One to Series Two. Second, the NASP test showed excellent reproducibility between the two testing sites. Maximum force and pullout force at 0.10-in. end slip showed an $R^2 = 0.97$ or higher between both FWC and OU results, and also between Series One and Series Two. Pullout force at 0.01-in. end slip matched reasonably well, but not nearly as good. The best indication of NASP test repeatability came from the pullout force measured at 0.10-in. end slip because it not only had an $R^2 = 0.97$, but also a best fit linear regression line that matched very closely to the line of a "perfect" test with 100% correlation.

Conclusions of the study were that the NASP pullout test was the most reliable, both in terms of repeatability and reproducibility. Furthermore, the NASP test had the least variation for pullout force measured at the maximum value or 0.10 in. end slip and had the most variation for pullout force measured at 0.01-in. end slip. Results of the PTI test showed the exact same trend. The author's only recommendation was the NASP pullout test be further developed as a quality control test, as it was clear from this set of findings that it was superior to the Moustafa or PTI pullout tests.

2.1.2.6 Russell and Brown (2004)

Russell and Brown (2004) used the same methodology as the NASP Round Two testing (Russell and Paulsgrove, 1999b) to further develop the NASP [Strand] Bond Test. This round of testing also included rectangular beams and transfer length measurements to check bond quality of 10 different strand sources. The 10 strands used were all 0.5-in., Grade 270 low-relaxation strands. In addition to the rectangular beam tests, this testing program again included three different pullout tests: the Moustafa Test, the PTI Bond Test, and the NASP Bond Test. The Moustafa and rectangular beam specimens were tested at Coreslab Structures Inc. (CS). PTI and NASP pullout tests were performed at both the University of Oklahoma (OU) and at Florida Wire Cable (FWC) to test their.

All mixes used for the beams and pullout specimens were designed to achieve a minimum of 3500 psi and a maximum of 4000 psi at the time of testing (18 to 24 hours after casting). The Moustafa test used a concrete mix, the PTI test used a neat mortar mix, and the NASP test used a sand-cement mortar mix. The mix design was held constant for tests being performed at multiple locations. The cement used for all tests was a Type III cement. The sand used was from Oklahoma and was supplied by the Dolese Bros. Co. for testing. PTI and NASP specimens were cast as documented previously in the NASP Round One and Two testing protocols (Russell and Paulsgrove, 1999a, 1999b) and used the same mix proportions. Testing procedures and specimen setups for the NASP and PTI tests are also documented in NASP Round Two. The specimens were cured in a temperature- and humidity-controlled chamber between 70-74^{o}F and 48-52% relative humidity. The Moustafa pullout blocks were cast according to Logan (1997). The rectangular beams were each 18 ft long with a cross section of 6.5 in. x 12 in. Two beams designs were used: one containing minimal shear reinforcement and one 0.5-in. longitudinal prestressed strand, and the second containing “heavier” shear reinforcement (#3 bars spaced at 6 in. on-center) and two 0.5-in. longitudinal prestressed strands. Each set of tests consisted of six specimens per strand source. This was consistent for all forms of testing, including all three pullout test methods and the rectangular beam testing.

The results of the testing program again showed that the Moustafa test results provided the lowest correlation between specimens cast at the different testing sites. This poor correlation between testing sites made it impossible for the author to recommend an acceptable bond criteria for minimum pullout strength. However, the Moustafa test was able to predict relative strand performance among strands tested at the same location using the same mix. The PTI pullout test showed similarly poor correlation, but not to the same severity. Results from the PTI tests conducted by FWC showed a high standard deviation and did not match up well with the tests performed at OU. The author concluded that the PTI test is still a poor quality control test, despite being a better bond predictor than the Moustafa test. The best bond test conducted by these researchers was the NASP [Strand] Bond Test as it showed the strongest correlation between testing sites. The 0.10-in. end slip value again proved to be the most statistically sound indicator, as was the case from NASP Round Two testing. The correlation was lower in Round Three (R^2 = 0.78) than in Round Two (R^2 = 0.98), but the transfer length correlation was proven to be relatively strong in this current testing procedure. The overall conclusion of the report was that the NASP [Strand] Bond Test was the most reproducible and repeatable bond test currently developed. The author also found good, direct correlation between NASP pullout values and transfer lengths of the rectangular beams. Further research was recommended by the author to develop the test into a more robust strand bond acceptance test.

2.1.2.7 Russell (2006)

Russell (2006) documented the research done in the NASP Round Four testing and further refined the NASP pullout test to determine whether or not it was an acceptable quality control test for assessing a strand's bond-ability to concrete. The research performed in this study consisted of both refining the test protocol as well as a set of blind round-robin tests at Oklahoma State University (OSU), Purdue University (PU), and the University of Arkansas (UA). The NASP pullout testing protocol was introduced in the NASP Round Two testing (Russell and Paulsgrove, 1999b) and used in the NASP Round Three testing (Russell and Brown, 2004). This protocol was refined in Round Three testing and used in NASP Round Four testing (Russell, 2006). The Standard NASP [Strand] Bond Test came from the findings of this Round Four research.

OSU performed testing on 10, 0.5-in. and two, 0.6-in., Grade 270 low-relaxation strands. PU performed testing on four, 0.5-in. and one, 0.6-in. strands. UA performed testing on six, 0.5-in. strands. Testing protocol and batching specifications are identical to those listed in previous NASP pullout tests except those noted here. Changes to the test included specifying the mortar flow value and tightening the mortar strength window. Mortar used in testing must meet a flow range of 100 to 125. Mortar strength must meet a range of 4500-5000 psi. The NASP [Strand] Bond Test also specifies the specimens be tested between 22 and 26 hours after casting.

Sand used to develop the NASP [Strand] Bond Test was obtained from the Dolese Bros. Co. in Stillwater, Okla. The cement used to develop the NASP [Strand] Bond Test was a Type III cement from Lafarge North America. Steel holders affixed to the 18-in.-long steel can were used to hold the steel strand specimens in the center of the 5-in.-diameter steel cans. Mortar was used to make both the NASP specimens and mortar cubes for testing mortar strength. Mortar for the NASP pullout specimens was consolidated using a mechanical vibrator, and mortar for the cube specimens was consolidated using the rubber tamper conforming to ASTM C109.

Differences of mortar strength were tested to see the effect on the NASP pullout strength. This was done by varying the w/c ratio from 0.4, 0.45, and 0.5. Mortar mixed with "a w/c of 0.45

was selected as the ‘best chance’ to produce mortar strengths at mid-range of the allowable strengths.” It was also determined that a higher mortar strength directly correlates to a higher pullout strength, based on tests ranging from 4000-6000 psi cube strengths. This effect was more prominent on strands that were higher bonding. The effect of load control vs. displacement control was also tested. Load control was tested at 5000 lbf/min and displacement control was tested at 0.10 in./min. It was determined that load control does not give the accurate “softening” or declining portion of the force vs. end slip curve that displacement control does. Due to this, the author still recommended using a displacement control with a rate of 0.10 in./min to run the NASP [Strand] Bond Test. Mortar flow value was tested and it was found that as water content increases, so does flow of the mortar. The range of 100 to 125 mortar flow value was recommended based on the w/c of 0.45. A flow that is out of range could indicate a problem with mixing procedure, or the cement or sand used in that specific batch. The flow is also required to be taken directly after batching, as results of this study found that flow “decreases significantly over time in the fresh state.”

The blind round-robin testing was performed at OSU, PU, and UA. Different sands and cements were used at each of these sites based on the availability at each testing location. Despite these differences, the sand was required to conform to ASTM C33 and the cement was required to conform to ASTM C150. Based on results of tests performed at each location, the NASP [Strand] Bond Test was determined to be repeatable. Overall test criteria and specifications listed in this review as well as NASP Round Two testing and NASP Round Three testing were determined to be a good indication of strand bond performance for 0.5-in. and 0.6-in. strand. Acceptance limits were set to be 10,500 lbf for the average of six strand specimens that make up a single test, with none of the specimens performing worse than 9,000 lbf. This criteria is based on results of transfer length data from prisms cast in the NASP Round Three testing program (Russell and Brown, 2004). The author recommended the strand bond test be adopted by both the Oklahoma Department of Transportation (ODOT) and the AASHTO LRFD bridge design manual. The author also recommended each strand producer in the United States have its strand certified using the NASP [Strand] Bond Test to prove its product conforms to the quality control standards specified here.

2.1.2.8 Ramirez and Russell (2008)

Ramirez and Russell (2008) looked extensively at the transfer, development, and splice length of 0.5-in.-diameter and 0.6-in.-diameter prestressing strands. The research was broken primarily into four phases: refinement of the NASP [Strand] Bond Test, transfer length measurements, development length tests, and lap-splice testing using mild steel reinforcement. Despite being very important research in their own right, the latter three phases do not fall within the research scope of this chapter. Therefore, only the first phase (refinement of the NASP [Strand] Bond Test) was reviewed.

The Standard Test for Strand Bond – formally known as the Standard Test Method for the Bond of Prestressing Strands – the authors looked at what was developed by Russell in April 2006 and is presented in the previous section. The main changes to the 2006 protocol were to the specimen preparation and test procedures. Blind, round-robin testing was again done at Oklahoma State University and Purdue University for this testing program. Five, 0.5-in.-diameter and two 0.6-in.-diameter strand sources were used for this series of refinement tests. Results again proved to be very repeatable. When a linear regression of the pullout results between the two sites was done, an $R^2 = 0.92$ was found relative to the “perfect fit” line indicating strong reproducibility among testing sites. The authors attributed this “demonstrable” reproducibility to the refined test protocol and systematic specimen preparation.

The authors again recommended the standard test for strand bond be adopted by AASHTO into the *LRFD Bridge Design Specifications*, based on the repeatability and reproducibility shown. The authors called for AASHTO to require the strand producers to be able to certify the bond-ability of the strand using the Standard Test for Strand Bond. A strand is considered acceptable for the Standard Test for Strand Bond if the average of the six 0.5-in.-diameter strands is at least 10,500 lbf and no one specimen is below 9,000 lbf. These values were determined from transfer and development length tests. For 0.6-in.-diameter strands, the average of the six strands must be at least 12,600 lbf and no one specimen can be below 10,800 lbf.

2.1.2.9 Peterman (2009)

The work done by Peterman (2009) presents the need for a simple strand bond test that can be used as a quality assurance (QA) measure rather than for quality control (QC) purposes. The test proposed in this paper asserts that this test would fulfill a need recognized by the Precast/Prestressed Concrete Institute (PCI) to verify the bond of prestressing steel when using

SCC mixes, but that the QA test is also valid for conventional concrete mixes. The test was to meet some very basic criteria in order to be simple enough for almost anyone to conduct, yet be accurate enough that results would be a good indication of bond performance. Original test specimens began with a cross-section of an 8-in.-wide by 6-in.-tall rectangular beam with one 0.5-in., Grade 270 strand cast into the section at a depth, d, of 4.5 in. No shear reinforcement was placed in the beams. Shallowness of the beam allowed the required loads to remain small enough to be lifted by a forklift. The width relative to the depth of the beam allowed for a stable section during applied loads with no concern of lateral-torsional buckling. The width also gave a large compression zone relative to the depth of reinforcing strand "which served to increase the strain of the prestressing steel at nominal capacity." Total spans of the beams were 11.5 ft with a constant moment region of 2 ft at mid-span. This length was "purposefully chosen so that the embedment length at each end would be about 80% of the calculated development length of the member." This allowed for an expected bond failure and reduced the chance of a flexural failure.

Loading for the test consisted of suspended concrete blocks hanging from nylon straps that formed the boundary for the constant moment region (2 ft at mid-span). For the various specimens, maximum nominal capacity ranged from approximately 5000-6000 lbf, depending on the strength of the concrete and other design factors. Bearing conditions consisted of one, 0.5-in. neoprene bearing pad at one end and one 0.5-in. Teflon-coated neoprene bearing pad located on top of a 1/8-in. steel plate to reduce horizontal restraints. These pads were located with their outer faces a distance of 2 in. from the ends of the beam, making the total clear span 11 ft 2 in. Design capacities of the beams were found using the methods of ACI 318 and AASHTO LRFD Bridge Design Specifications for prestressed beams. Testing of the specimens consisted of casting the beams using "standard batching, placement, consolidation, curing, and detensioning methods." The strands were then ground flush with the end of the beam. The beams were gradually loaded to 85% of the maximum nominal moment capacity of the section, using the aforementioned nylon straps and concrete blocks. Initial, visual end slip measurements were taken from the end of the beam, documenting any initial cracks. This dead load was sustained for a minimum of 24 hours to observe any more end slip, cracking, or other distressing of the beam. The beam was finally loaded to full nominal moment capacity for 10 minutes. The beam passed if it did not collapse. The only specified loading rate for the 85% nominal moment was "gradual."

Peterman recommended at least two beams be cast simultaneously, as initial research for this paper indicated a “significant reduction” in bond was observed when the beam was tested in the first three weeks after casting. One or both of the beams should be tested at or after 28 days. An alternative trapezoidal section was also allowed and dimensioned in the paper. After 25 rectangular sections and 13 trapezoidal sections had been tested at the time of the paper, the author observed “no consistent differences in ultimate load-carrying capacity of the two sections.” This test served as a quality assurance test for the final product of pretensioned concrete beams. Other ASTM tests – pullout tests, material gradation tests, cement content tests, or strand material tests – are all quality control tests that assure the material entering the final product meets minimum requirements. However, prior to the above study, no test existed to assure the quality of the final, prestressed product.

2.2 Smaller Diameter Strand and 5.32-mm Wire Pullout Tests

2.2.1 Introduction

Very little research has been done on 5.32-mm-diameter steel prestressing wires. In fact, so little that the background information presented in the following papers contained some smaller diameter steel fibers (0.6 mm and 1.0 mm fibers) and some larger diameter steel bars (10 mm and 16 mm) to go along with the 5.32-mm research. Research regarding small diameter, three-wire strand was also investigated as a way to gain insight into any problems these smaller diameter specimens might present.

The primary objective of the research performed to date has been to accurately model the surface between the prestressing wires and concrete. From an academic standpoint, this is avaluable and fruitful endeavor. From a manufacturing standpoint, this previous research did little to develop a reliable quality control test or to even propose an acceptable criterion for bond-ability of wires. Despite this limitation on the available literature, valuable information and conclusions from an experimental laboratory viewpoint were able to be extracted. Among these findings were insight into indentation depth related to bond performance; the importance of indentations (and their geometries) vs. a smooth surface; and the importance of a simple, accurate, and repeatable pullout bond test.

2.2.2 Wire Bond Research

2.2.2.1 Galvez et al. (2010)

Galvez et al. (2010) developed a plastic cohesive-frictional model to be used to exhibit the bond between concrete and indented prestressing wires. Experimental testing was also performed to compare results to the analytical model. The author noted the model was developed for prestressing wires with chevron indents, but the model can be expanded to include three- and seven-wire strands.

The ABAQUS model took into account both the cohesive crack model that deals with the splitting of the concrete due to radial pressure of the wire, and the bond model which takes into account the bond interface between the concrete and prestressing steel. The cohesive crack model used a bilinear approximation of the material-softening function which “relates the stress acting across the crack faces to the corresponding crack opening.” The bond model was idealized with two simplifications. First, the stress distribution was taken as uniform along the length of the wire instead of being concentrated at each individual indent. Second, the deformation of the concrete in the bond zone was idealized based on the fracturing of the concrete at each ridge.

The experimental portion of this research included a series of push-in tests to compare to the results of the numerical analysis. The push-in-type test was used because it directly includes the radial expansion of the wire that relates to the bond performance. The specimens tested were rectangles 60 mm wide with three different thicknesses (14 mm, 22 mm, or 30 mm). Two embedment lengths were chosen to be 400 mm for the long specimens and 64 mm for the short specimens, to study the differences between non-uniform bond stresses for longer members. The wires used were all 4 mm, nominal diameter with three different indent depths (shallow = 0.015 mm, medium = 0.050 mm, and deep = 0.105 mm). The specimens were tensioning the wire to 17 kN of force, casting the concrete and letting it cure, and transferring the prestressing force to the concrete by moving the actuator at a rate of 0.3 mm/min. Longitudinal shortening of the prism, wire end slip measurements, widths of cracks, and release load were all recorded during the testing (the release of the prestressing force).

The ABAQUS model accurately predicted results of the experimental testing for both the long and short embedment-length specimens. The model used the mechanical properties of the steel and concrete, depth and geometry of the wire indentation, and parameters of the bond interface to predict the response of the concrete. Test specimens and the model both showed that deeper indents resulted in better bond, but also showed the highest bond stresses led to a higher propensity to split the concrete. The authors were pleased with the accuracy of the model and the way it predicted the bond of the wires to the concrete. However, they recommended that more work be done to extend it to “full-scale structural elements” and applications for prestressing strand. Further work also needs to be done to see if different indent geometries (varying indent side angles, indent orientation, etc.) will work accurately with the model as well.

2.2.2.2 Chanvillard (1999)

Chanvillard (1999) developed a model that attempted to take into account the effect that nonstraight wires had on pullout results. It also took into account the effect of steel deformation during the course of the pullout test. The wires were tested both as straight sections and as nonstraight combinations of wire segments in which a straight, then semicircular, then straight section of wire was tested. The mathematical model was developed using general static equilibrium principles acting on a curved fiber element. Approximations were made to the model to take into account components of normal and tangential forces on the curved surface using small-angle theory. Deformations of the steel during testing (slippage of the fiber) were taken into account using energy mechanics so as to provide a more accurate model. The work done by the external forces is balanced by the dissipation of energy internally through deformations. This slippage (deformation) causes a change in curvature because the dead end was still anchored – in that it has not yet slipped at this exact instance of time – and the live end had begun to travel around a curved surface. The deformation of the fiber was approximated and used to calculate the strain tensor matrix. This strain tensor, coupled with knowledge of the stress tensor, allowed the researcher to calculate the deformation energy in the fiber during pullout testing. Including knowledge of cohesion, friction, and finally, integrating the whole model along the fiber length, allowed the researcher to predict the theoretical pullout load-displacement curves.

The wires used to verify the validity of the model were 0.6 mm and 1.0 mm in diameter with varying bonded lengths. Straight pullout tests were performed to see how closely the model matched results from previous research work. Then, nonstraight pullout tests were done to verify the curvature component of the new model. Three tests for each wire diameter, bond length, and configuration were performed and averaged, and then compared to the theoretical model’s predictions. The testing was done in a sand-cement mortar mixture using different w/c ratios of

0.4, 0.5, and 0.6. It was determined through testing that the cohesion, friction, and modeling slope were intrinsic parameters of fiber behavior. The main conclusion of the testing and modeling was the “fiber [surface] geometry is the main parameter for reinforcement efficiency that it offers in cracks.” This finding is an interesting point with respect to the different force vs. slip relationships that exist between seven-wire strands and 5.32-mm-diameter wires, especially since the tests were conducted in a sand-cement mortar mixture.

2.2.2.3 de Almeida Filho, El Debs, and El Debs (2008)

de Almeida Filho, El Debs and El Debs (2008) performed two separate types of pullout tests in concrete on 10-mm- and 16-mm-diameter bars (not strand) to examine the different bond-slip properties for different concrete mixes. The wires used were both 500 MPa (72.5 ksi) yield stress. Each test configuration was performed three times and averaged to obtain bond strength vs. slip results.

The first type of pullout test performed consisted of unconfined, cylindrical specimens loaded at the bottom with end slip measured at the opposite end (top) using an LVDT. The specimens were clamped into the machine and loaded in displacement control at a rate of 0.01 mm/s for the 10-mm bars and 0.016 mm/s for the 16-mm bars. The LVDT itself was affixed to the steel bar and measured slip relative to the top surface of the concrete. Two test specimens were developed for the different bar diameters. The 10-mm bars were cast into a 100-mm-diameter tube with a 50-mm bond length. Similarly, the 16-mm bars were cast into a 160-mm-diameter tube with an 80-mm bond length. Both specimens appear to have a total length of approximately twice their bond length, i.e. 100 mm and 160 mm total length, respectively, but this dimension was not given in the paper. Some sort of bond breaker appeared to be in place to account for this discrepancy between bond length and total specimen length.

The second type of pullout test performed consisted of two concrete prisms with a steel bar cast near the tension (bottom) surface. This bar acted as the only structural piece holding the two prisms together. Bond breakers were placed at both ends of both specimens so that a bonded length of 10 bar diameters was achieved. A hinge was placed at the top and the setup was loaded very close to midspan using a short spreader beam. This setup allowed for a bond slip failure as the exposed bar at midspan pulled out before the concrete was in danger of crushing. The specimens containing 10-mm bars were approximately 650 mm in total length with a cross section 180 mm by 180 mm. The specimens containing 16-mm bars were approximately 1100 mm in total length with a cross section of 240 mm by 240 mm. The beams were instrumented with an LVDT at each of the outside concrete edges. Again, these LVDTs were attached to the steel bars themselves and measured the slip relative to the concrete surface.

The researchers analyzed the bond stress data at 0.01-, 0.1- and 1.0-mm end slip and at the ultimate bond stress for the steel bars. All specimens slipped, but some of the steel specimens ruptured prior to a full pullout failure. The bond stress vs. end slip results were relatively consistent between the cylindrical and prism specimens for each individual test setup. Normalized for stress, the smaller diameter bars exhibited slightly higher stresses than the larger bars. (Note: This trend was also exhibited between similar bonding strands and wires; the bond stress increased as the total diameter decreased.) In general, the beam specimens had less slip and less bond stress than the cylindrical specimens. However, the authors attribute this difference in part to the method of testing (prisms were tested in flexure, whereas the cylinders were tested with pure axial force). The author determined the two different pullout methods to both be fair predictors with low variability in the results therefore making them both reliable tests. The authors recommended the cylindrical test be used in place of the beam test because of its relatively simple setup and good accuracy. The beam test was deemed to be much more difficult to setup and control the important variables, particularly the concrete cover and bonded length.

2.2.2.4 Gustavson (2004)

Gustavson (2004) investigated what parameters affect the bond of three-wire prestressing strands. These 6.5-mm (.255 in.) three-wire strands were tested in both pullout and push-in tests, and the cohesion, friction, and other mechanical actions were documented. The pullout tests were simple, un-tensioned tests whereas the push-in tests were pretensioned to 28 kN force. The researchers were careful to document the strand's behavior far beyond the ultimate applied force to determine the bond-slip relationship. The research also modified the surface of some strands using Teflon spray, plastic film, oil lubricant, and sandblasting to test the effect of the surface condition on bond.

The three-wire strands had indents according to the FIB (European) bond report. The European code specifies an indentation depth and indentation spacing. The authors also modified the three-wire strands by changing the spacing (indentations per unit length went down by approximately half). All strands were cast into 50-mm-diameter steel and plastic tubes with a total height of 75 mm and a wall thickness of 1 mm. A 25-mm aluminum bond break was placed at the bottom of the test strand length, leaving a bonded strand length of 50 mm. The specimens were consolidated using a vibrating table, and were covered with plastic lids on the top and bottom. (Note: no mention was made as to how the plastic caps were fastened at the bottom to prevent bleed water or concrete seepage.) Nine specimens were cast for each of the pullout and push-in tests.

The pullout tests were loaded at the bottom and the end slip was measured at the opposite (top) end. Displacement control was used for these tests with a load rate of 2.2 mm/min. All specimens were tested after 24 hours curing time. Compressive cylinders were used to test the strength of the concrete, which was determined to be 55 MPa at the time of testing. Rotation was permitted by use of a thrust bearing on the load frame. The amount of rotation was recorded using a wire displacement transducer attached to the tube. The length of the wire wound at the end of the test, along with the radius of the specimen, was used to calculate the angle of rotation. Rotation was found to begin shortly before the maximum load was reached. The rate of rotation was also constant once it began. The force vs. end slip graphs given in the data raised some questions. The graphs indicated that slip was measured up to a distance of 70 mm of free end slip; however, the specimens themselves were only 75 mm long (including a 25-mm bond breaker). This would imply the tests were run until the strands were completely pulled out of the bottom of the specimen. This begs the question: physically, how could end slip measurements still be taken with the entire mass of concrete obstructing any data acquisition devices?

Push-in tests were loaded at the top and the displacement measurements taken with a displacement transducer at the top. Again, rotation of the specimens was allowed. Prestress force was released from 28 kN down to 0 kN at a rate of approximately 1 mm/min at the time of testing (24 hours after casting) by use of two wrenches and a person manually rotating them. Concrete strength at the time of testing was between 21 and 35 MPa. Load vs. end slip curves were built using the difference between the displacement measured on the strand and the displacement of the top surface of the concrete as the prestressing force was released.

The author found the strength of the concrete did not affect the bond capacity of the three-wire strands tested. This finding is different than those of previous research suggesting that concrete strength does affect the bond capacity of indented, deformed bars (presumably rebar). The author hypothesized that different failure mechanisms govern deformed bars and coiled strands. The author concluded that adhesion is not affected by indentations, nor does adhesion affect the overall ultimate pullout force required as it is broken long before the peak load is reached. The second main conclusion was that friction (surface condition) between the concrete and steel is substantial in bond performance. However, the author stated that the mechanical action of the strand indents was the biggest factor affecting bond capacity. This bond capacity can be increased by properly spacing the indents which will aid in mechanical interlock, or can be decreased by having too many indents per unit length, which can cause a high propensity for cracking and thereby reduce bond capacity.

2.3 Conclusion

The NASP [Strand] Bond Test has been revised numerous times to make results of the strand pullout test more meaningful. The first draft dated August 2001 was only used to assess 0.5-in.-diameter, seven-wire strands. This test protocol was used for NASP Round III research (Russell and Brown, 2004). The second version dated May 2004, included provisions for 0.6-in. seven-wire strands. This procedure was used in NASP Round IV testing (Russell, 2006). With some minor changes in protocol, the current version of the test is a result of both NASP and NCHRP funding and was proven to be reproducible. This test is called the Standard Test Method for the Bond of Prestressing Strand (Russell, 2006; Ramirez and Russell, 2008). However, the NASP [Strand] Bond Test is still not specified for any 0.375-in. or 3125-in. strand. As such, no standard bond test for 0.375-in. strand or 0.3125-in. strand exists. Furthermore, no such standardized 5.32-mm wire bond test is in place either.

At present, prestressed concrete railroad ties are being manufactured primarily with 5.32-mm wire but also with smaller diameter (less than 0.5 in.) strand. However, no standard bond tests exist to quantify the performance of these small diameter reinforcement types used by the concrete railroad tie industry. To suit the needs of the concrete railroad tie industry, the scope of the Standard Test for Strand Bond must be expanded for strands smaller than 0.5-in.-diameter and a standard 5.32-mm-diameter wire bond test must be developed. With this in mind, the research presented in this report is focused on two main goals:

1. Develop a standard test method to assess the bond of 5.32-mm-diameter wire.
2. Provide evidence in favor of expanding the Standard Test for Strand Bond to include smaller diameter strands or to develop a similar standard for these smaller diameter strands.

Chapter 3 - Reinforcement, Storage, and Cleaning Procedure

3.1 Reinforcement

A total of 19 reinforcements were used in this testing program. Thirteen prestressing wires and six prestressing strands from seven different steel manufacturers were used in the un-tensioned pullout tests described in Chapters 4 and 5. Upon receipt of the reinforcement, the 13 wires were given generic labels ranging from [WA] through [WM]. Likewise, the six strands were given generic labels ranging from [SA] through [SF].

All wires were 5.32-mm-diameter, Grade 270, low-relaxation prestressing wires with various indent geometries. One wire contains no indents (smooth). The remaining 12 wires are indented and conform to ASTM A881. All strands were Grade 270, low-relaxation strands. Some strands were 5/16-in.-diameter and some were 3/8-in.-diameter. Additionally, some were three-wire strands and some were seven-wire strands. A picture of all of the wires can be seen in Figure 3.2 and a picture of all of the strands can be seen in Figure 3.3. A close up view of each wire is shown in Figure 3.4 and a close up view of each strand is shown in Figure 3.5. Each reinforcement's ultimate force, ultimate strength, cross-sectional area, and modulus of elasticity as provided by the manufacturer can be seen in Table 3.1.

The internal nomenclature for pullout testing was developed to quickly and easily identify key information. A typical specimen employed the naming system shown in Figure 3.1.

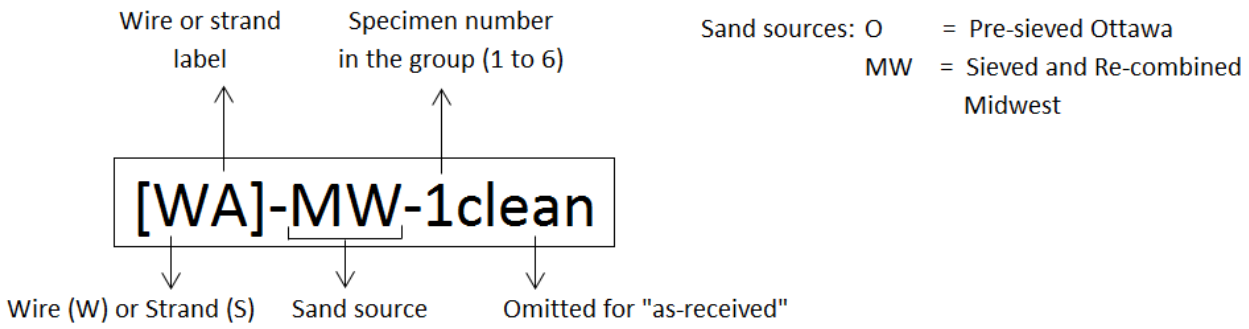


Figure 3.1 Pullout specimen nomenclature

Figure 3.2 Samples of the 13 wires with various indentation geometries

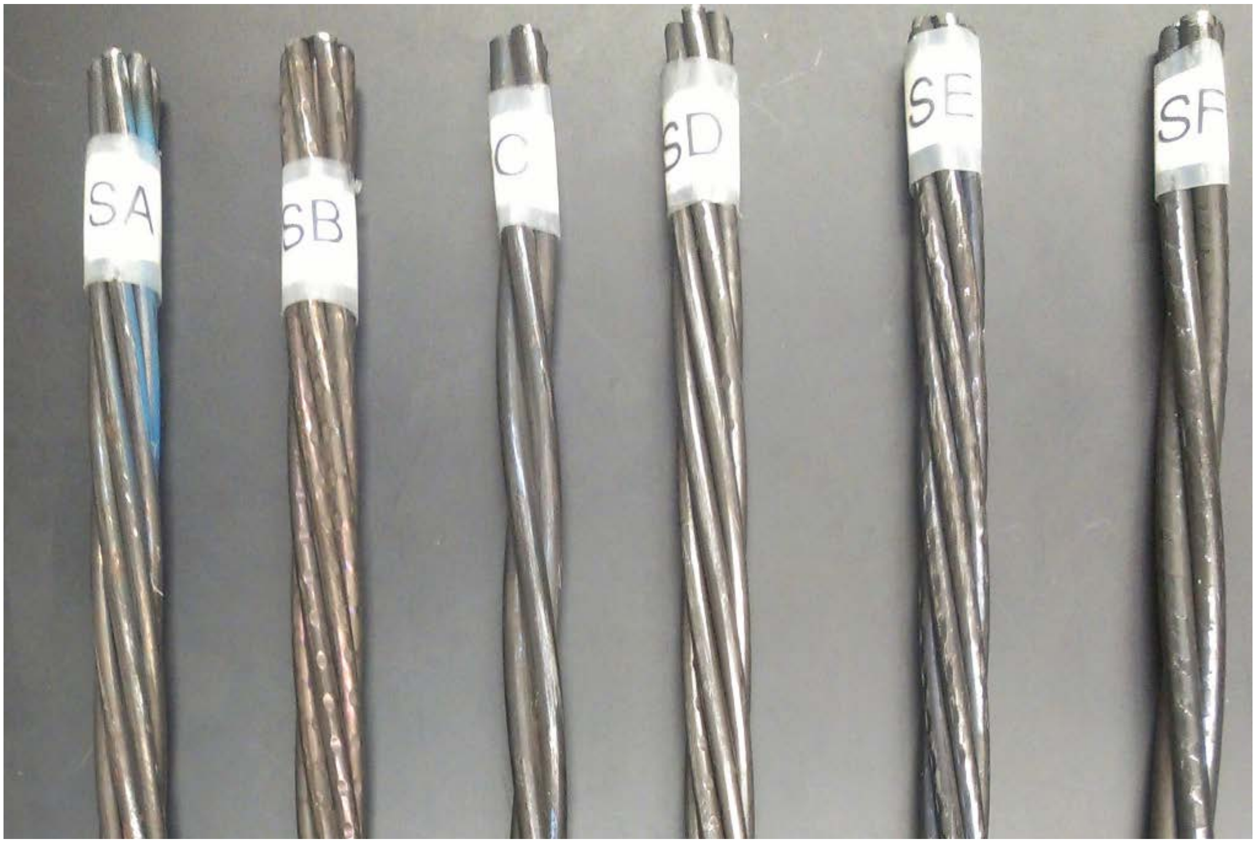


Figure 3.3 Sample of the six strands with various indent geometries and diameters

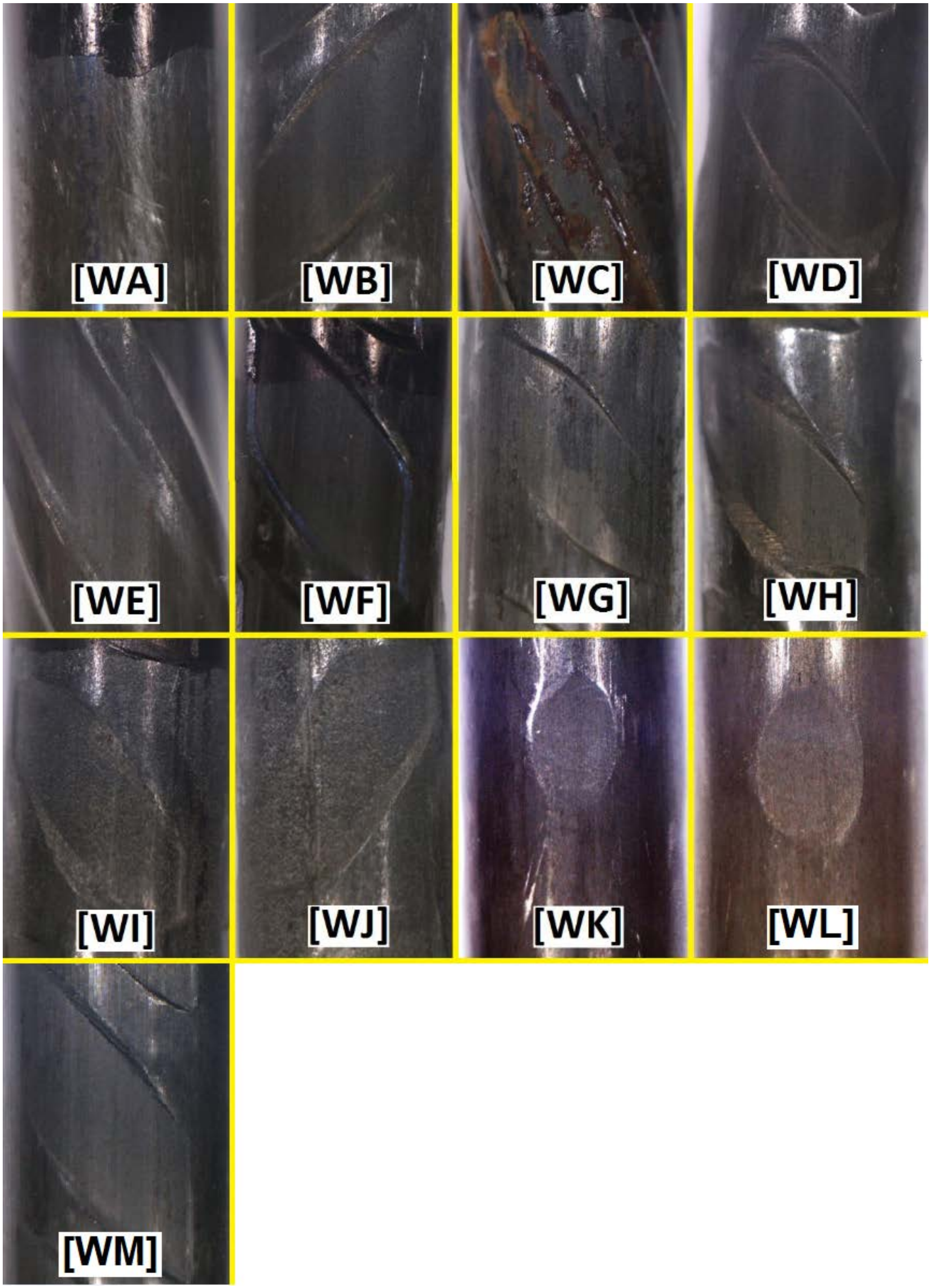


Figure 3.4 Close up view of wire specimens

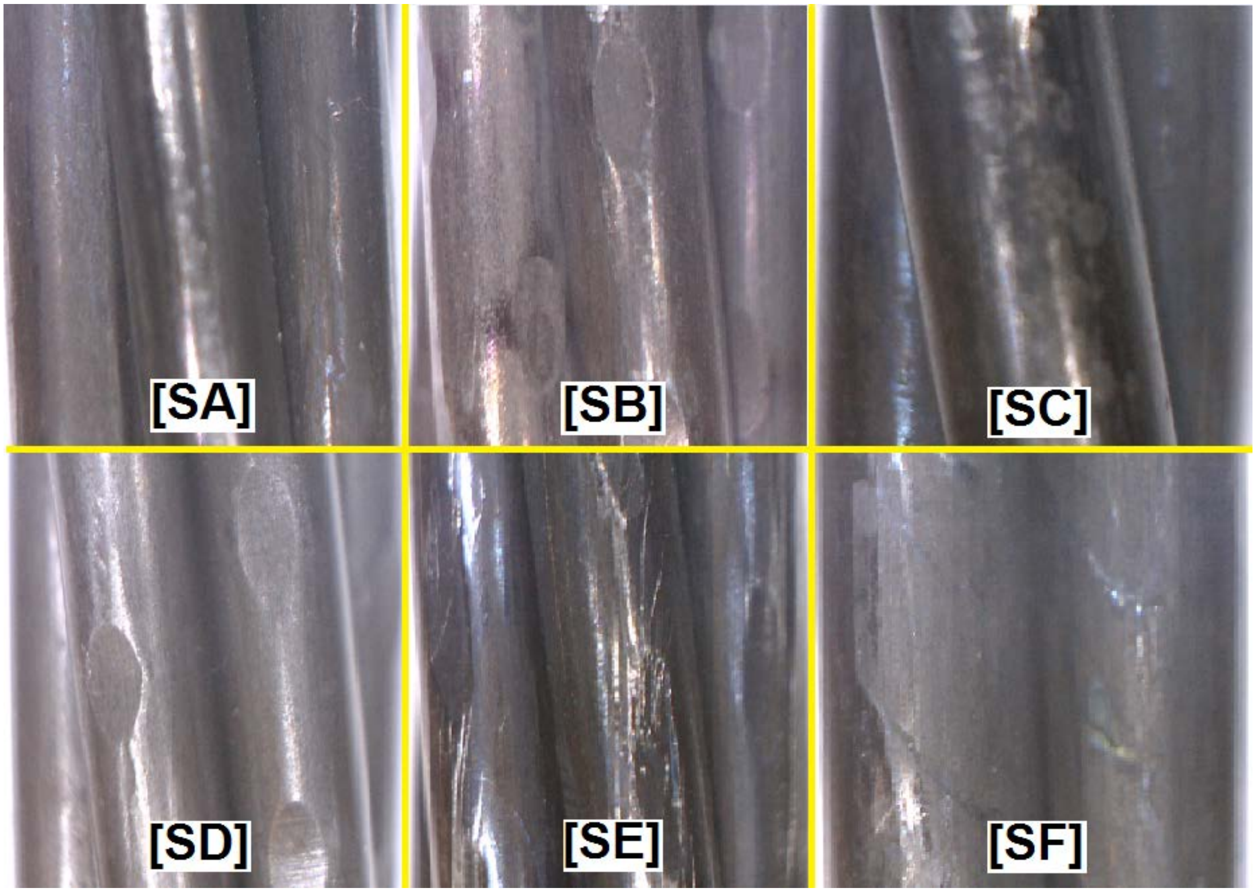


Figure 3.5 Close up view of strand specimens

Table 3.1 Ultimate strength, area, and modulus of each reinforcement

Reinforcement		Indentation Type	Ultimate Tensile Force (lbf)	Ultimate Tensile Strength (ksi)	Cross-Sectional Area (in^2)	Modulus of Elasticity, E (ksi)
Wire	[WA]	Smooth	10184	293.5	0.0347	29700
	[WB]	Chevron	9712	281.7	0.0345	30510
	[WC]	Spiral	9892	290.3	0.0341	28400
	[WD]	Chevron	9696	275.5	0.0352	30120
	[WE]	Spiral	9258	268.6	0.0345	28570
	[WF]	Diamond	9280	269.2	0.0345	29000
	[WG]	Chevron	9376	271.0	0.0346	30300
	[WH]	Chevron	9438	271.2	0.0348	29870
	[WI]	Chevron	9389	279.5	0.0336	29000
	[WJ]	Chevron	9702	276.9	0.0350	28600
	[WK]	4-Dot	9839	284.6	0.0346	29430
	[WL]	2-Dot	9711	280.9	0.0346	29480
Strand	[SA]	3/8" 7-Wire, Smooth	23661	278.4	0.0850	29000
	[SB]	3/8" 7-wire, Indented	23793	279.9	0.0850	29000
	[SC]	5/16" 3-wire, Smooth	15871	272.7	0.0582	29000
	[SD]	3/8" 7-wire, Indented	24630	288.1	0.0855	29090
	[SE]	3/8" 7-wire, Indented	23069	272.4	0.0847	28100
	[SF]	3/8" 3-wire, Indented	18550	285.4	0.0650	28560

3.2 Reinforcement Storage

Upon delivery to Kansas State University, all 19 reinforcements were stored in separate polyvinyl chloride (PVC) tubes in 25-foot lengths. Wires were stored in 3-in.-diameer PVC tubes and strands were stored in 4-in.-diameter PVC tubes. Silica-based desiccant packets were also placed in the PVC tubes to prevent any rusting and preserve the reinforcements' "as-received" surface condition for testing. These 25-foot pieces were cut into shorter lengths for testing. If any delay between cutting and testing was expected, specimens were stored in smaller (shorter) PVC tubing until the time of testing. A picture of the PVC/reinforcement storage racks is shown in Figure 3.6.

Figure 3.6 Reinforcement storage rack

3.3 As-Received vs. Cleaned Reinforcement

Of great importance is investigating what portion of a reinforcement's bond performance can be attributed to indent geometry and what portion attributed to surface condition. The researchers expect the wires and strands to be affected to different degrees by these two effects (indent geometry and surface condition), which were investigated by testing the reinforcements in both their "as-received" and "cleaned" conditions. The "as-received" specimens provided a baseline reading for the expected bond performance of each reinforcement as they were received from their respective suppliers. The "cleaned" specimen tests were performed on bare steel by removing rust, oils, and surface lubricants with an acidic solution. This process allowed the researchers to better separate out the bond attributed to surface condition from the bond attributed to indent geometry.

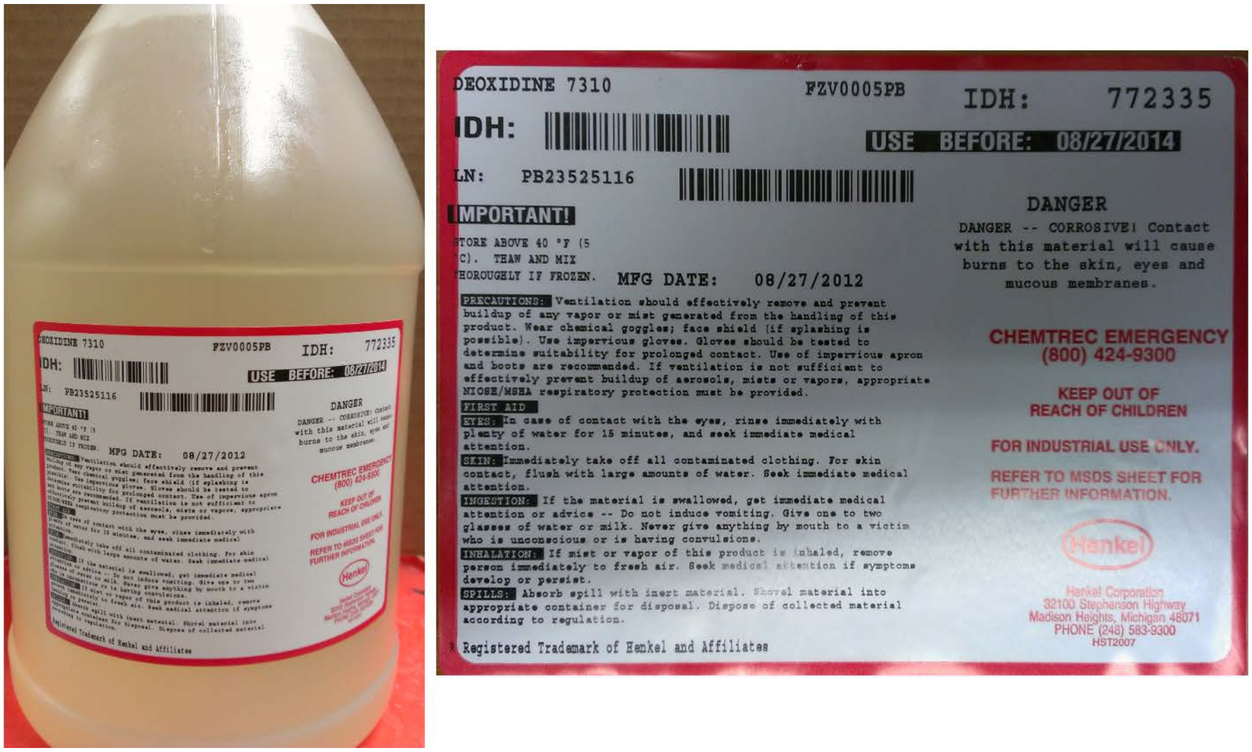
All 13 of the wires and all six of the strands were tested in an “as-received” condition. To preserve the “as-received” surface condition, the reinforcements were placed in PVC tubes with silica-based desiccant packets to prevent any rusting. All “as-received” specimens were prepared and tested shortly after being removed from the PVC tubes. For more information on the storage procedure, see Section 3.2.

Seven of the wires and all six of the strands were tested in a “cleaned” condition. To test the reinforcements in a “cleaned” condition, they were removed from the PVC tubes and cleaned using a hydroxyacetic and citric acid, Deoxidine 7310 obtained from the Henkel Corporation. The cleaning solution can be seen in Figure 3.7. The acid solution was then diluted with water using a 10 parts water to one part acid ratio. The total volume mixed each time was approximately 24 fl. oz. contained in a plastic spray bottle. A new volume of solution was mixed for each day reinforcement samples were cleaned. All of the chemicals and steel specimens were handled with nitrile gloves to avoid skin contact. Each reinforcement specimen was cleaned using the following procedure:

1. Rinse with water from a hose with a spray nozzle.
2. Spray with Deoxidine 7310 and water solution, and scrub steel surface by (gloved) hand.
3. Rinse with water from a hose with a spray nozzle.
4. Spray with Deoxidine 7310 and water solution. Let sit for approximately 15 seconds.
5. Scrub steel surface using a brass brush for approximately 30 seconds.
6. Rinse with water from a hose with a spray nozzle.
7. Dry steel specimen with clean cloth.
8. Stand specimen on end to allow excess solution to drain at the bottom.

This cleaning process was performed approximately 45 minutes before the steel was tied into the cans and approximately 90 minutes before mortar was poured. This allowed enough time for the solution to drain and dry, but not enough time for the steel to rust or become dirty again.

The visual effect of the cleaning process can be seen in Figure 3.8 to Figure 3.20 for all seven of the wires and all six of the strands.



DEOXIDINE 7310 FZV0005PB IDH: 772335

IDH:

USE BEFORE: 08/27/2014

LN: PB23525116

IMPORTANT!

STORE ABOVE 40 °F (5 °C). THAW AND MIX THOROUGHLY IF FROZEN.

MFG DATE: 08/27/2012

PRECAUTIONS: Ventilation should effectively remove and prevent buildup of any vapor or mist generated from the handling of this product. Wear chemical goggles; face shield (if splashing is possible). Use impervious gloves. Gloves should be tested to determine suitability for prolonged contact. Use of impervious apron and boots are recommended. If ventilation is not sufficient to effectively prevent buildup of aerosols, mists or vapors, appropriate NIOSH/MSHA respiratory protection must be provided.

FIRST AID

EYES: In case of contact with the eyes, rinse immediately with plenty of water for 15 minutes, and seek immediate medical attention.

SKIN: Immediately take off all contaminated clothing. For skin contact, flush with large amounts of water. Seek immediate medical attention.

INGESTION: If the material is swallowed, get immediate medical attention or advice -- Do not induce vomiting. Give one to two glasses of water or milk. Never give anything by mouth to a victim who is unconscious or is having convulsions.

INHALATION: If mist or vapor of this product is inhaled, remove person immediately to fresh air. Seek medical attention if symptoms develop or persist.

SPILLS: Absorb spill with inert material. Shovel material into appropriate container for disposal. Dispose of collected material according to regulation.

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REACH OF CHILDREN

FOR INDUSTRIAL USE ONLY.

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Henkel

Henkel Corporation
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Madison Heights, Michigan 48071
PHONE (248) 583-9300
HST2007

Figure 3.7 Chemical used in reinforcement cleaning process (Deoxidine 7310)

Figure 3.8 [WA] As-received vs. cleaned comparison

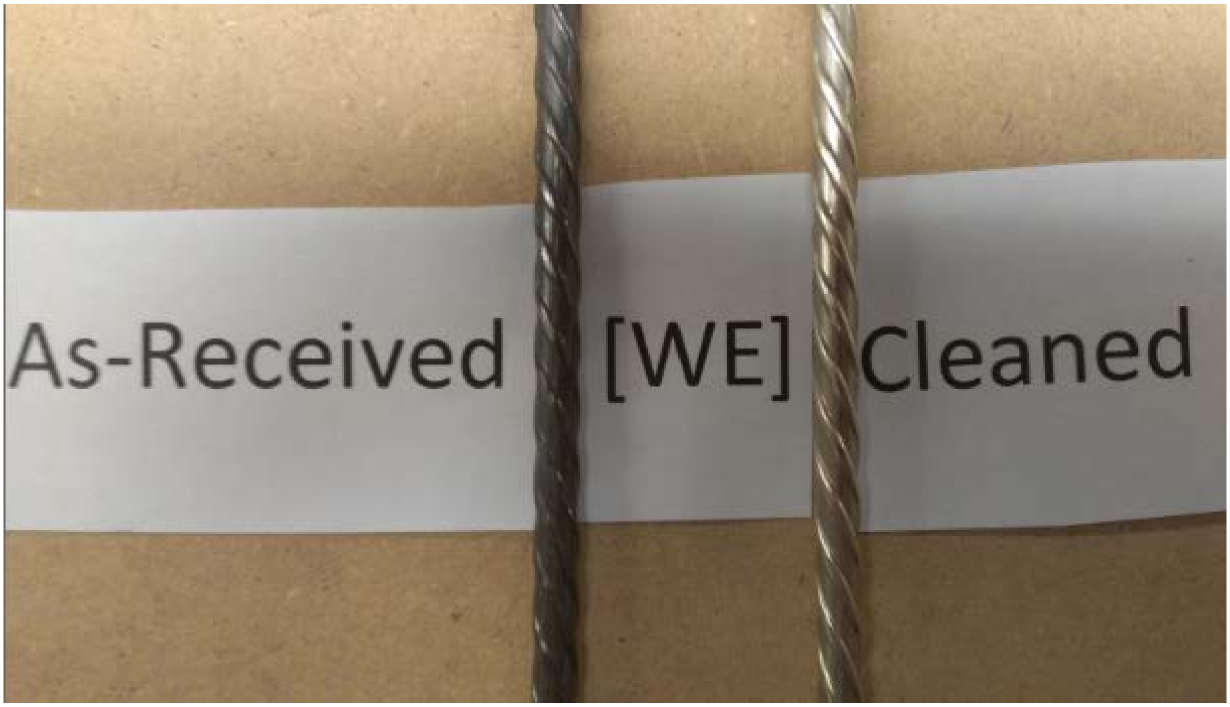


Figure 3.9 [WE] As-received vs. cleaned comparison

Figure 3.10 [WF] As-received vs. cleaned comparison

Figure 3.11 [WG] As-received vs. cleaned comparison

Figure 3.12 [WH] As-received vs. cleaned comparison

Figure 3.13 [WK] As-received vs. cleaned comparison

Figure 3.14 [WM] As-received vs. cleaned comparison

Figure 3.15 [SA] As-received vs. cleaned comparison

Figure 3.16 [SB] As-received vs. cleaned comparison

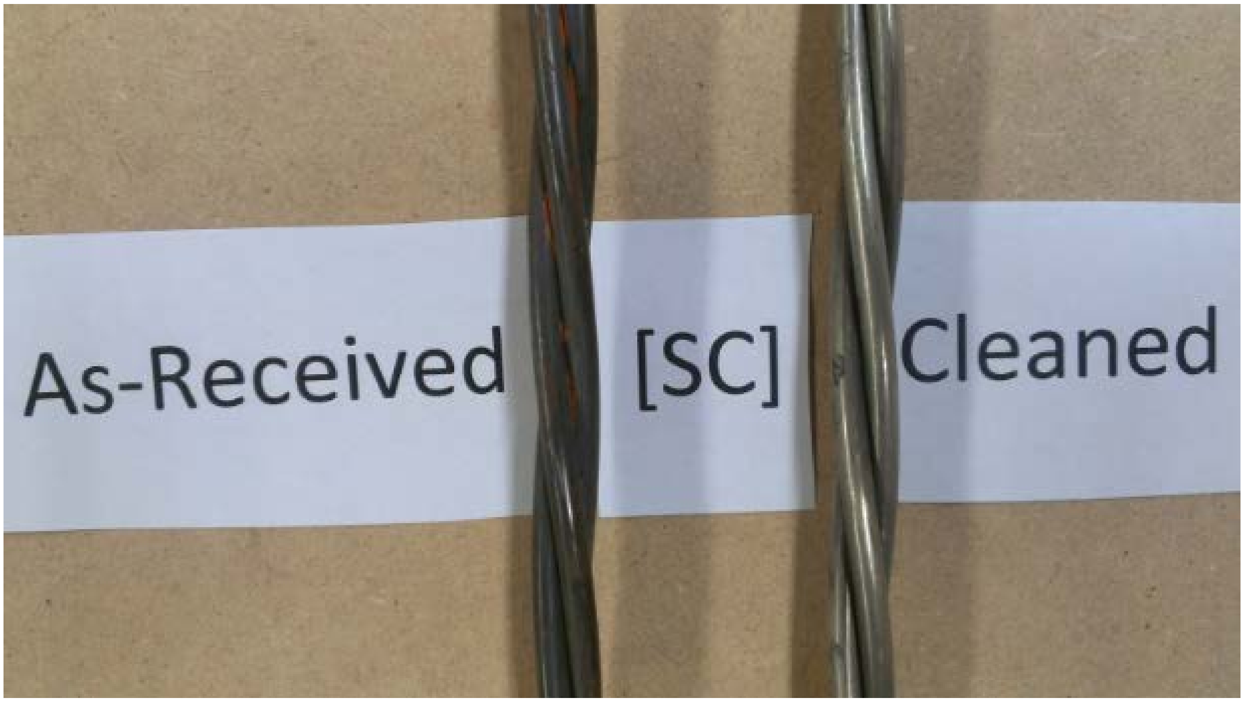


Figure 3.17 [SC] As-received vs. cleaned comparison

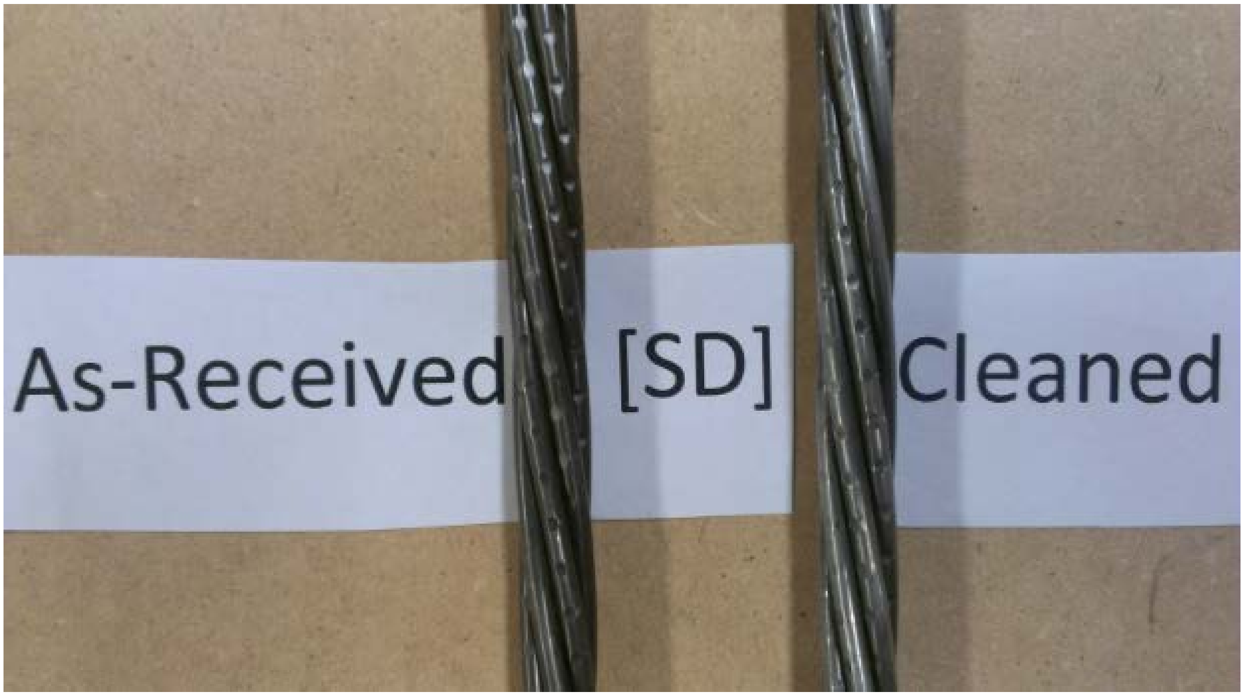


Figure 3.18 [SD] As-received vs. cleaned comparison

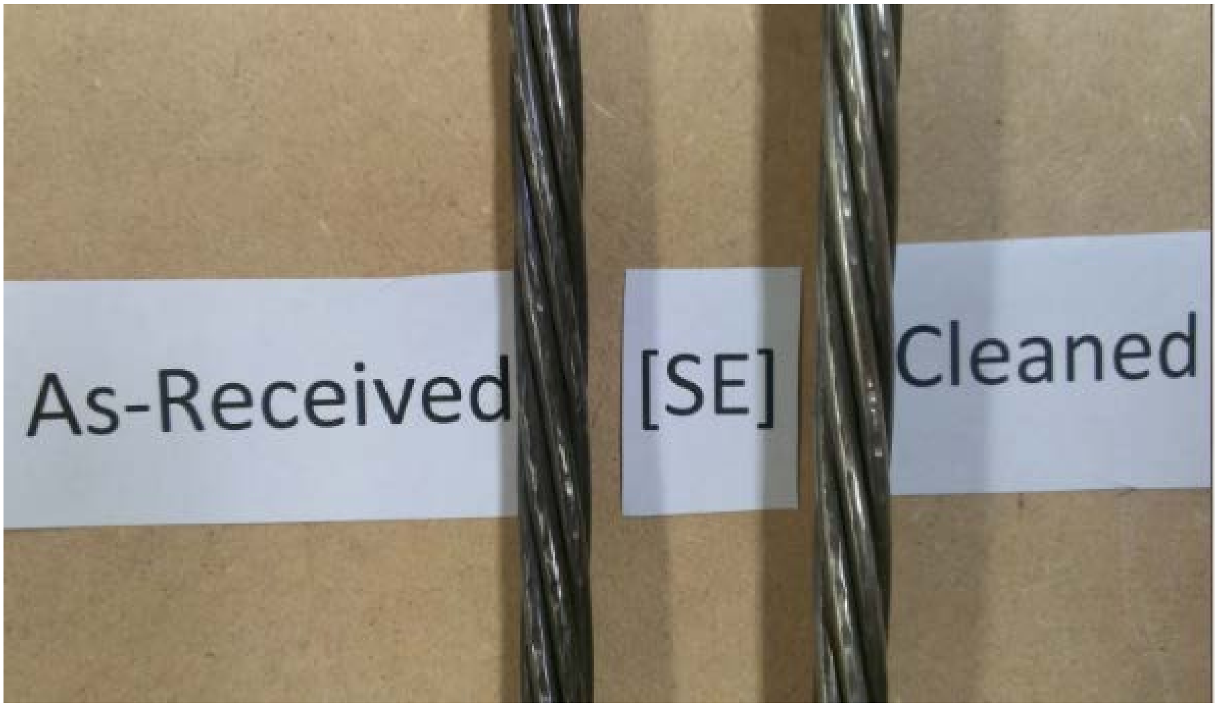


Figure 3.19 [SE] As-received vs. cleaned comparison

Figure 3.20 [SF] As-received vs. cleaned comparison

Chapter 4 - Lab Phase; Wire Pullout Testing (Un-tensioned Tests in Mortar)

Chapter 4 discusses test development, experimental program, results, and analysis of the lab portion of the wire bond pullout tests. These tests are un-tensioned and were performed in mortar.

4.1 Development of the Pullout Test

Development of a standardized 5.32-mm-diameter wire pullout test was done with two main research variables in mind: indent geometry and surface condition. A preliminary test was also run using both force- and displacement-control tests to decide which control type was best suited for the wire test. Two specimen sizes and two sand sources were tested until an appropriate combination of parameters was established to be repeatable. Finally, various testing on different parameters concerning the method were performed and are documented. All of these topics are discussed in the following section.

4.1.1 Preliminary Wire Specimen Size

The first specimen dimensions tested are shown in Figure 4.1. A 5-in.-outer-diameter tube with a 1/8-in. wall thickness was used for preliminary testing because this is the standard for 0.5-in.-diameter, seven-wire strand testing (Ramirez and Russell, 2008). Total tube length was 12 in. and a bond length of 9 in. based on prior testing conducted by the primary investigator. Wires WA, WB and WI were chosen as preliminary trials for developing the wire pullout test, based on depth and size of the indentation patterns provided by these three specimens. With widely varying indentation depths, the author hoped to produce a large range in bond performance, which the other wires being tested would most likely fall between. WA is a smooth wire and was hypothesized to be the low end of the bond performance. WI is deep chevron indent and was hypothesized to be one of the higher bonding wires. WB was chosen as an indent to be somewhere in between. The preliminary trials were tested using the concrete sand produced by Midwest Concrete Materials (“Midwest sand”) that comes from sand pits surrounding Manhattan, Kansas. These preliminary trials showed good variation between the three wires’ bond performances.

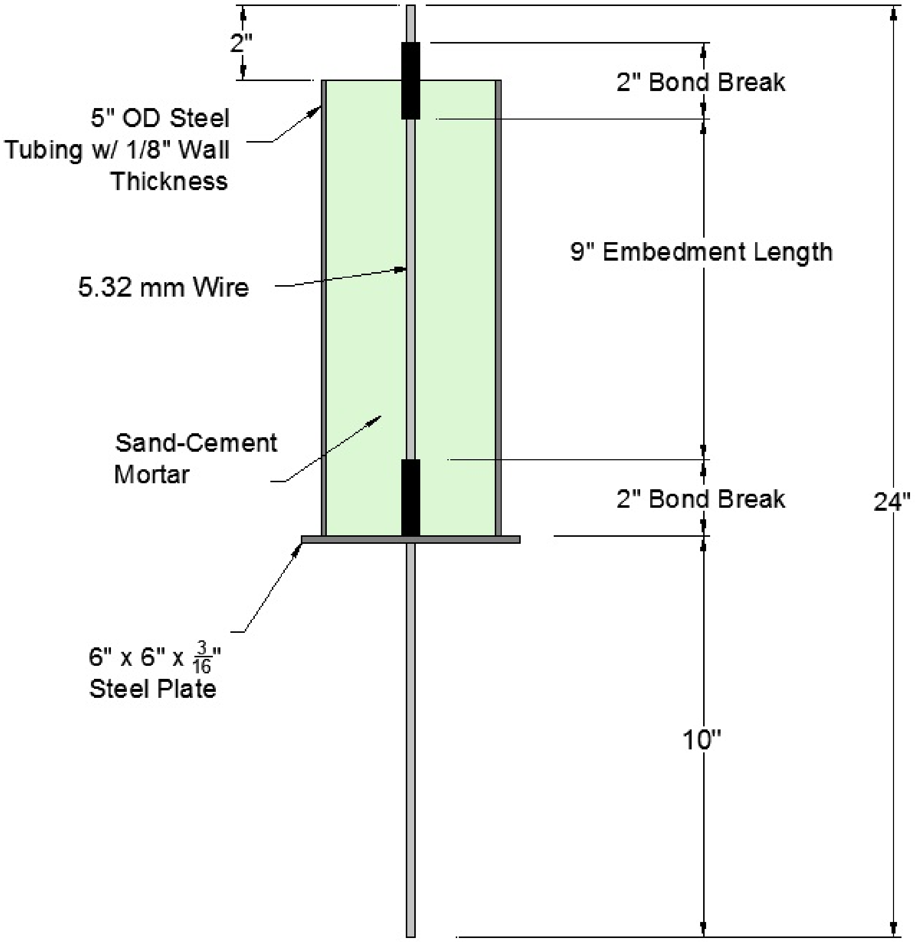
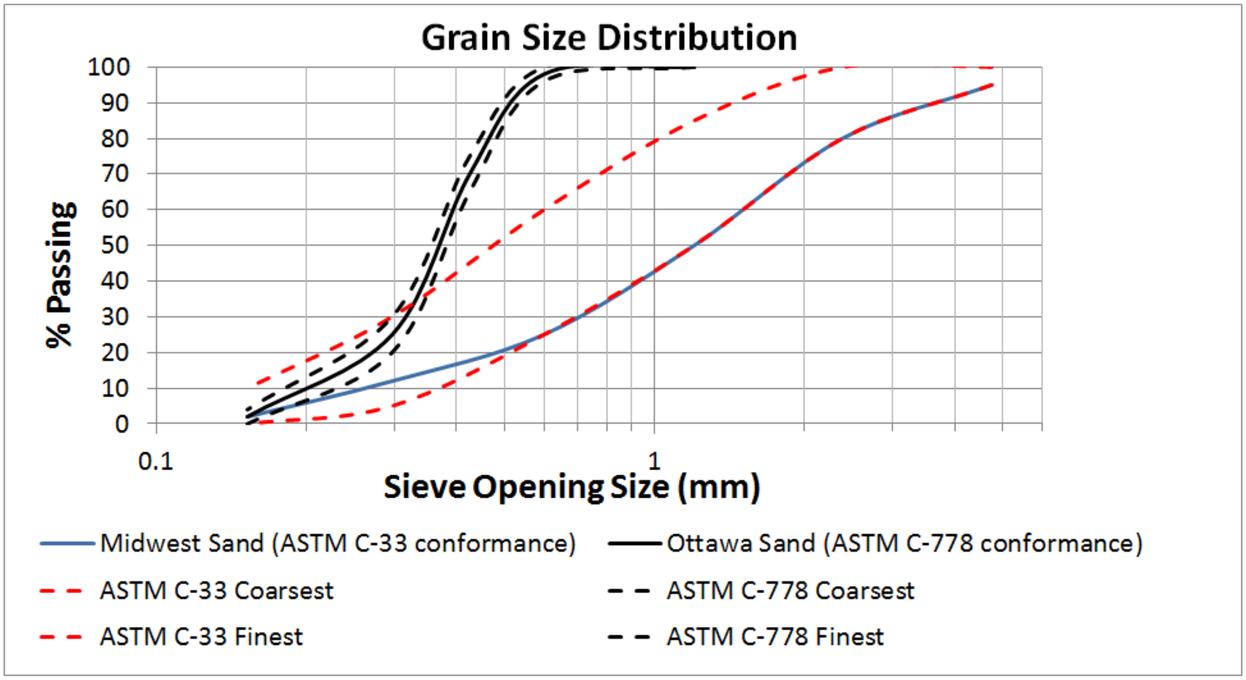


Figure 4.1 Preliminary wire pullout specimen dimensions

4.1.2 Sand Source (Ottawa Sand vs. Midwest Sand)

Two separate sand sources were used to develop the specimens. The first was a local Midwest (MW) sand conforming to C33. This is concrete sand produced by Midwest Concrete Materials (“Midwest sand”) that comes from sand pits surrounding Manhattan, Kansas. The grain-size distribution used in all Midwest wire batches is shown in Figure 4.2. This sand is inexpensive as it is found locally. The second sand used was supplied by Humboldt Manufacturing Co., Ottawa, Illinois. The sand was pre-sieved (conforming to ASTM C778) and arrived in 50-pound bags and boxes. Figure 4.16 shows a picture of the pre-sieved Ottawa sand used for wire pullout tests. This sand is expensive at approximately $50-$60 per bag.



GSD for Midwest Sand

Sieve #	Opening (mm)	% Passing	ASTM C-33 (% Pass)	
			Min	Max
4	4.75	95	95	100
8	2.38	80	80	100
16	1.2	50	50	85
30	0.599	25	25	60
50	0.297	12	5	30
100	0.152	2	0	10

GSD for Ottawa Sand

Sieve #	Opening (mm)	% Passing	ASTM C-778 (% Pass)	
			Min	Max
16	1.20	100	100	100
30	0.599	98	96	100
40	0.425	70	65	75
50	0.297	25	20	30
100	0.152	2	0	4

Figure 4.2 Sand gradations used for wire pullout specimens

4.1.3 Force Control vs. Displacement Control Test

Before the final mix proportions, specimen dimensions, and sand source could be established to obtain data uniformly, the author wanted to determine whether running the test in displacement control or force control gave more consistent results. In the comparable work conducted by Ramirez and Russell for seven-wire strands (2008), a displacement-controlled test was recommended. However, the author wanted to also investigate a force-controlled test because the required equipment would be less expensive and would allow more of the invested parties (wire manufacturers, tie manufacturers, and railroad owners) to readily perform the test.

Using the Midwest (MW) sand source and WI wire, 12 specimens – six in force control, six in displacement control – were tested the same day, using the same batch of mortar in alternating fashion. The force control tests used a loading rate of 2000 lbs/minute and the displacement control tests used a loading rate of 0.1 inch/minute. Both tests loaded the specimen at the bottom, while continuously monitoring and recording the applied load and free-end slip at the opposite (top) end using a linear variable differential transformer (LVDT).

Individual results of the force vs. end slip graphs for both the force and displacement control graphs are shown in Figure 4.3. Average results are shown in Figure 4.4. Average results with the highest and lowest bonding specimens omitted are shown in Figure 4.5. It can be seen that both control methods give almost identical data, especially in the ascending region. Thus, with cost and accessibility of the test equipment in mind, the author decided to use a force-controlled setup for the wire pullout test. From this point on, any wire test discussed in this paper was run in force control at a loading rate of 2000 lbs/minute. Full specifications of the pullout load frame capabilities (as well as the rest of machinery used for pullout testing) can be found in Section 4.2.5.

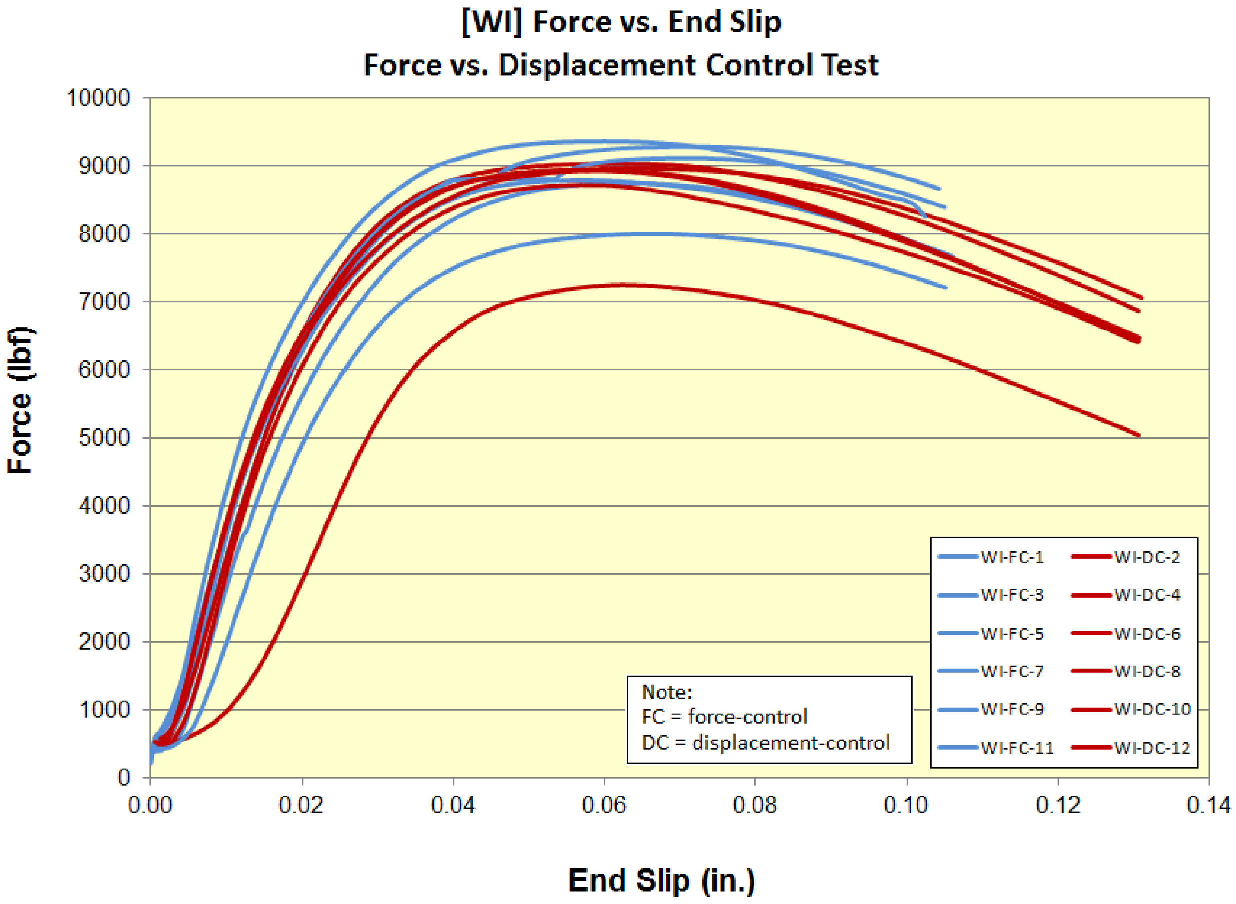


Figure 4.3 Individual results of force vs. displacement control test

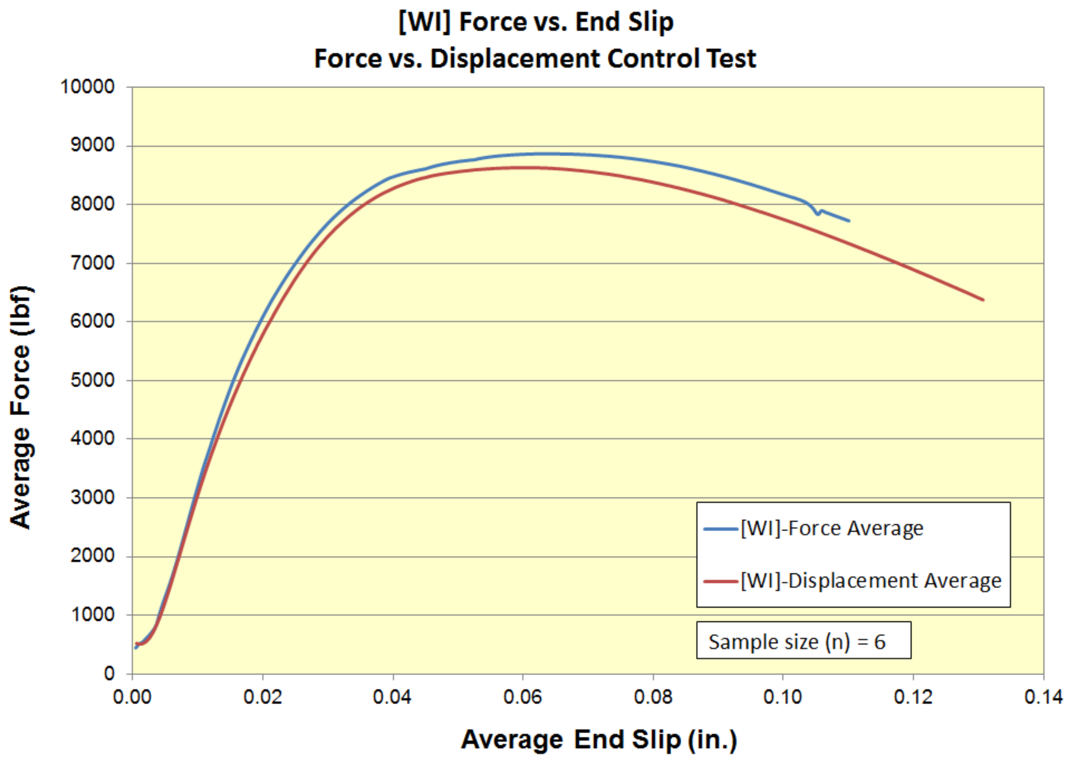


Figure 4.4 Average results of force vs. displacement control test

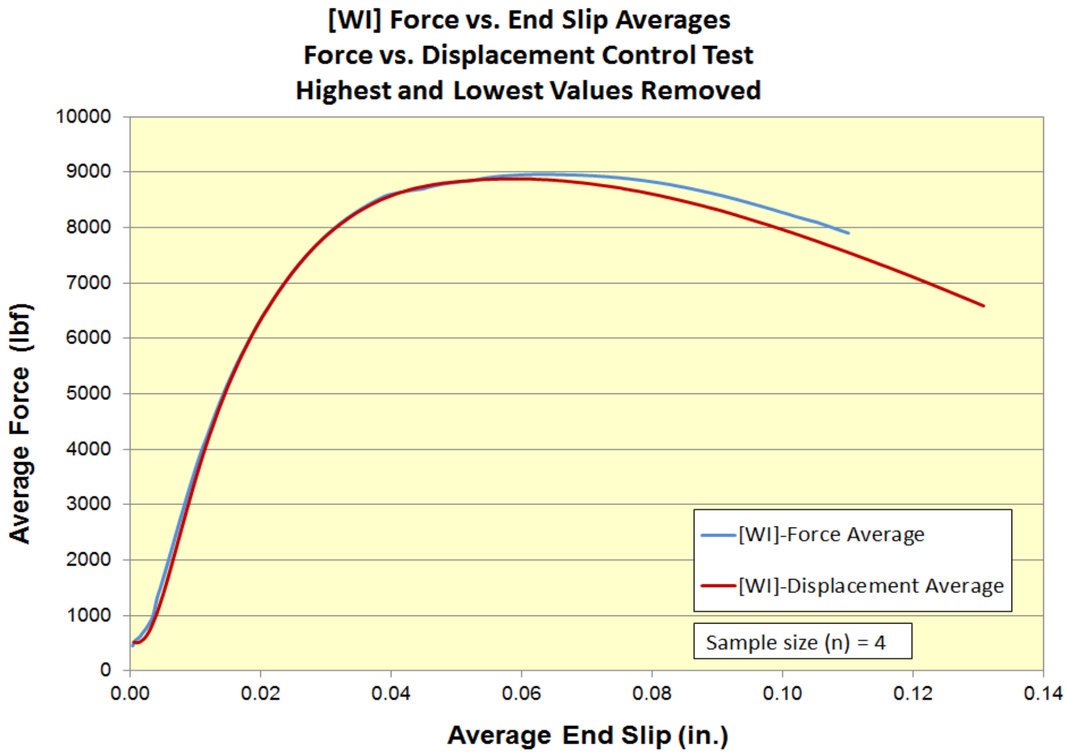


Figure 4.5 Average results of force vs. displacement control test (min and max excluded)

4.1.4 Rotation Allowed vs. Rotation Restrained Test

The Standard Test for Strand Bond prescribes the stiff test frame used for pullout testing must be “without torsional restraint” (Ramirez and Russell, 2008). In practice, this can be accomplished by adding a thrust bearing when connecting the pullout frame to the machine. The frame at Kansas State University has such a setup and allows for rotation of the specimens during testing, as can be seen in Figure 4.25.

To find whether or not this thrust bearing made a difference for wire pullout tests, half of the specimens were tested without torsional restraint (through use of the thrust bearing) and the other half with torsional restraint (by removing the thrust bearing). The two wires selected were WC and WE because of their spiral indent pattern. This pattern is similar to the spiral nature exhibited by multiple-wire strands. Six WC specimens and six WE specimens – three allowed to rotate and three prevented from rotating – were tested the same day, using the same batch of mortar.

The testing order was as follows. The three WC specimens allowed to rotate were tested first, and then the thrust bearing was removed from the pullout frame. Next, the three WC specimens prevented from rotating were tested, followed by the three WE specimens prevented from rotating. Finally, the thrust bearing was put back on the pullout frame and the final three WE specimens allowed to rotate were tested. Unsieved Midwest sand was used for these tests.

It was theorized the specimens not allowed to rotate would exhibit a slightly higher force when comparing the same levels of end slip because torsional forces would build up. Results of this test are presented in Figures 4.6 and 4.7 for wires WC and WE, respectively. As can be seen, the results appear very close. In the WC specimen, the hypothesis was proved correct in that the force at any given end slip is slightly higher when rotation is prevented, compared to when rotation is allowed. For the WE specimens, the force was almost identical for both cases (restricted and unrestricted torsion). Results of the test were not conclusive enough to warrant making this aspect of the wire pullout test different than the Standard Test for Strand Bond. It is the author’s opinion that testing facilities should be able to interchangeably run strand and wire pullout tests as smoothly as possible.

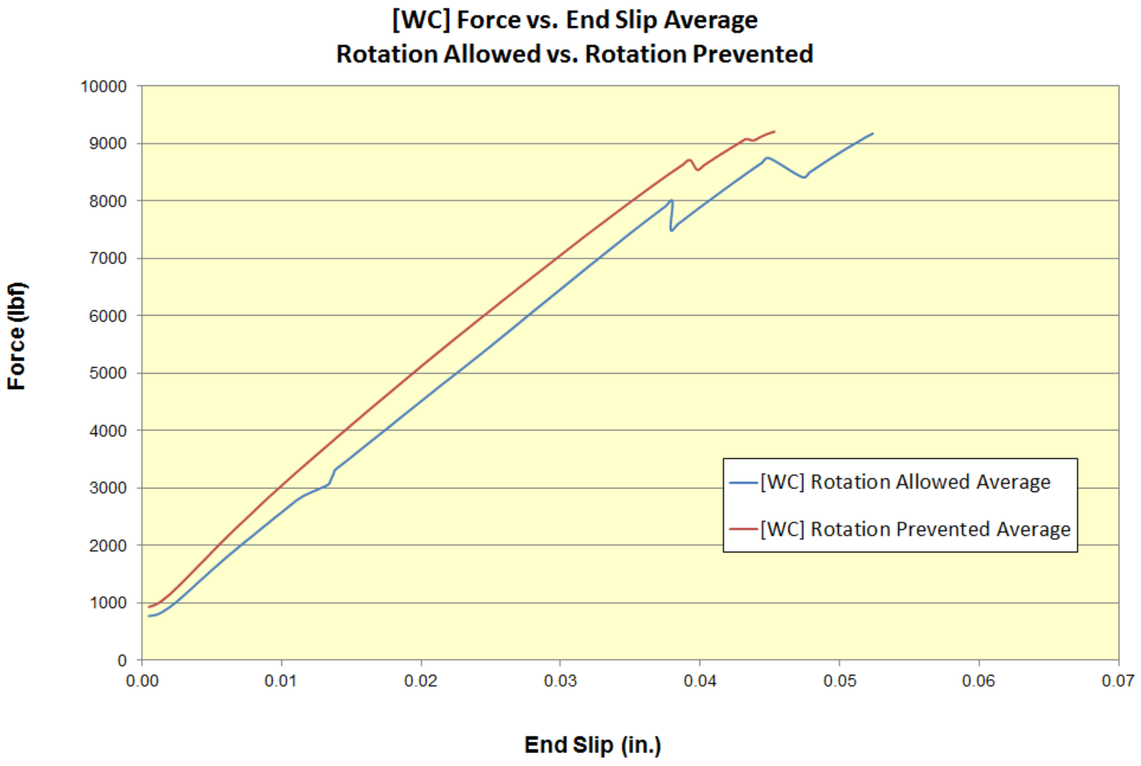


Figure 4.6 Results of [WC] rotational test

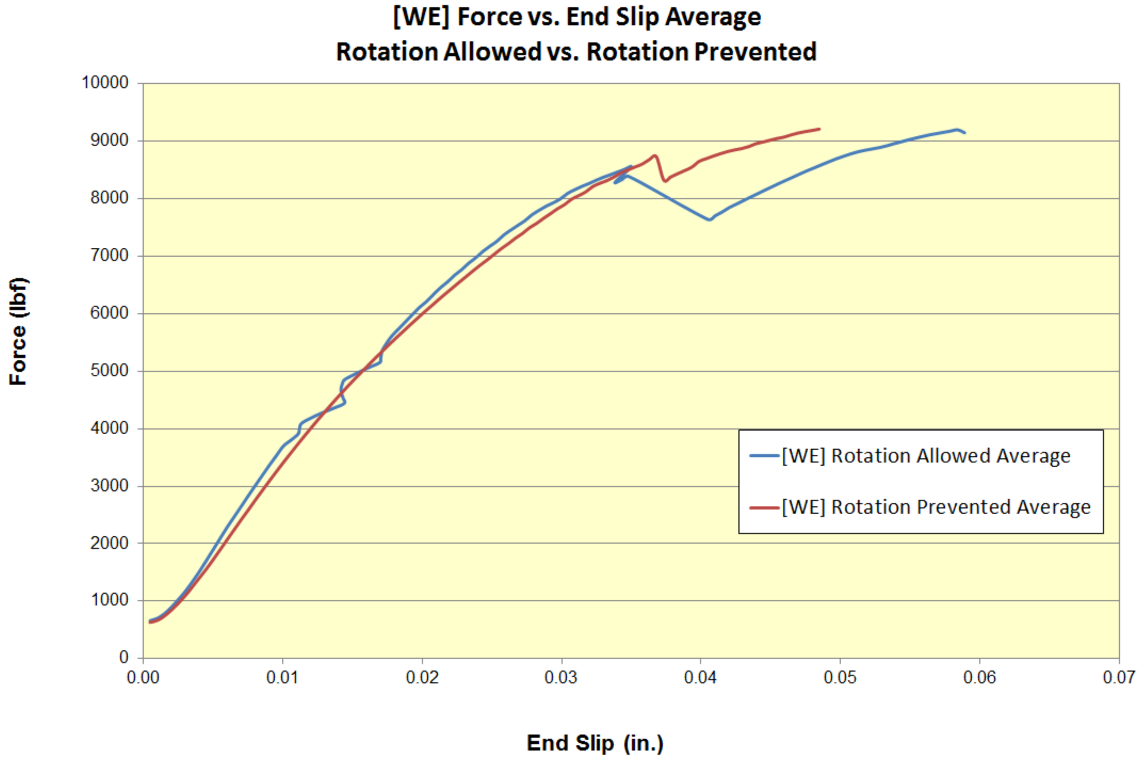


Figure 4.7 Results of [WE] rotational test

4.1.5 Finalization of Sand Source and Specimen Size

The specimen size described in Section 4.1.1, “Preliminary Wire Specimen Siz,” was tested for all 12 wires (WA through WL) being used to develop the test. The following parameters were used:

1. Force control used with a loading rate of 2000 pounds/min.
2. Rotation allowed by way of a thrust bearing on the load frame
3. Both sand sources were used to test six specimens of all 12 wires to determine which sand gave the most consistent results

When all 12 wires were tested using both Midwest and Ottawa sands, it was discovered a few of the wires were higher bonding than WI. This meant the highest bonding wires would fail by material rupture prior to pullout bond failure (the desired failure mode). Average pullout force vs. end slip results for the preliminary wire specimens using Midwest sand and Ottawa sand can be seen in Figures 4.8 and 4.9, respectively. Individual pullout vs. end slip graphs for each wire using each sand source can be seen in Appendix B.

Please note the test was stopped automatically using an MTS force limit of 9200 pounds to prevent rupturing wires and causing damage to the linear variable differential transformer (LVDT). This force was selected because it is below the ultimate load for all wires. Any test stopped early resulted in a truncated data set. Visually, this causes the average pullout force vs. end slip graph to exhibit jagged inconsistencies. Each “dip” in the graphs of Figures 4.7 and 4.8 represent one of the six specimens getting close to a rupture failure (more than 9200 pounds) before a pullout failure and the test being stopped.

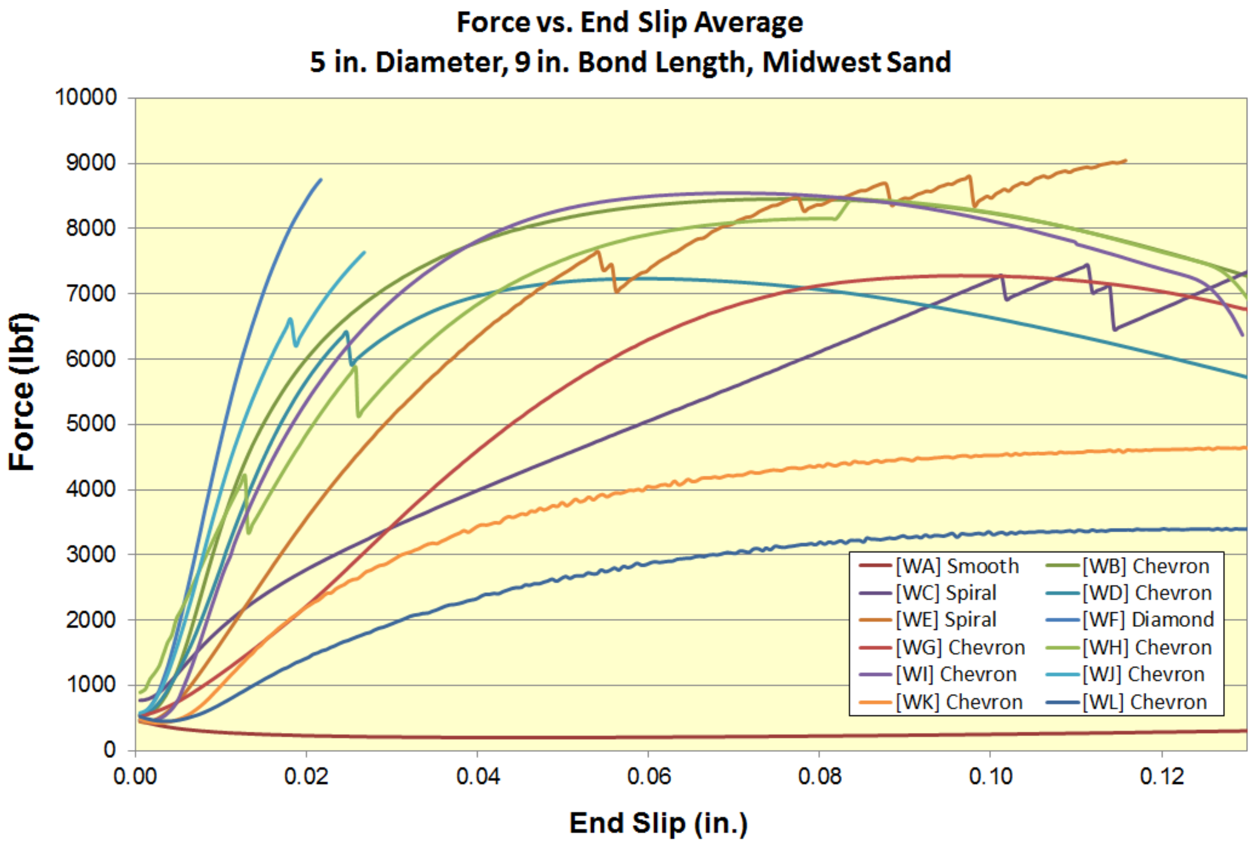


Figure 4.8 Force vs. end slip average test development (Midwest sand)

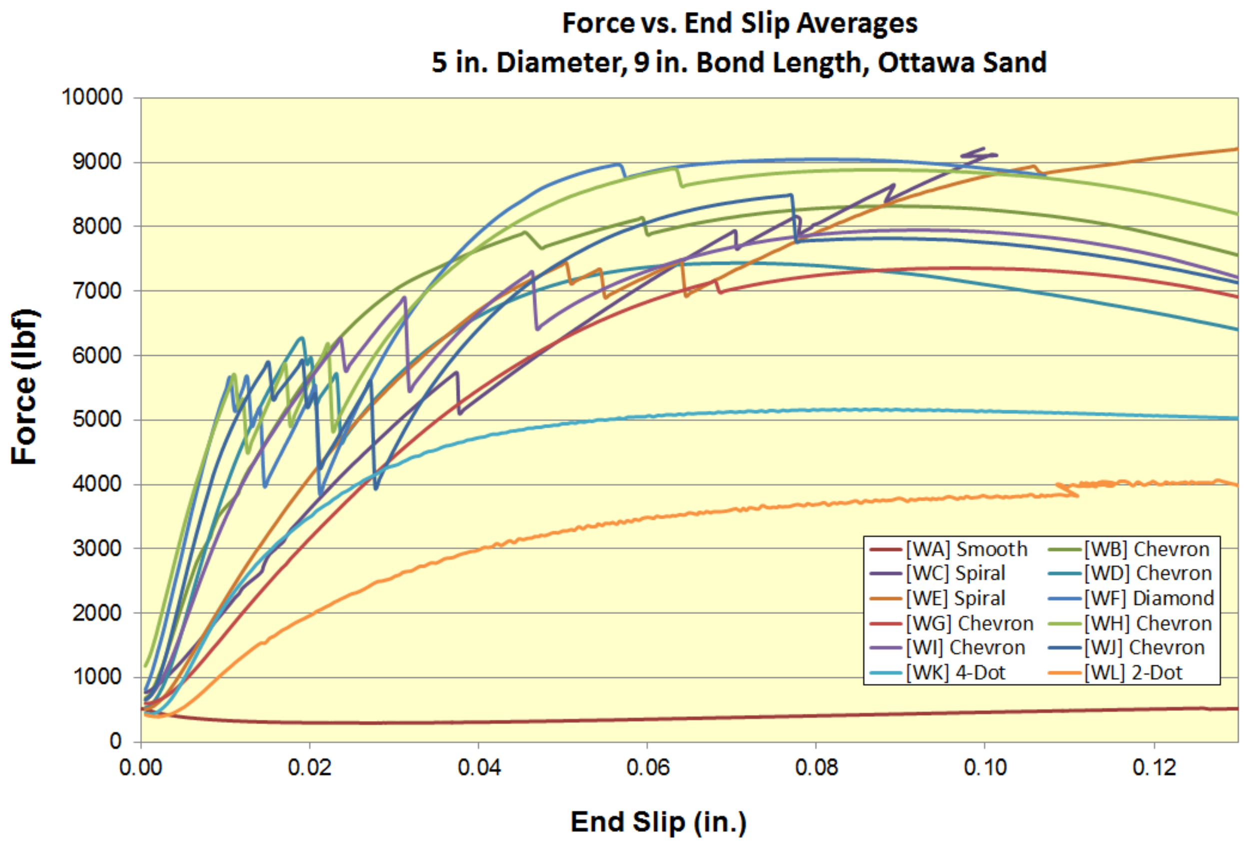


Figure 4.9 Force vs. end slip average test development (Ottawa sand)

Due to results of Figures 4.8 and 4.9, it was clear the bond length needed to be reduced to ensure a pullout failure for all wires in the study. To go about this, three steps were taken.

1. Determine which sand source gave the most repeatable results. This was the original intent of the first round of testing.
2. Vary the bond length using the highest bonding wire to determine the appropriate bond length.
3. If possible, reduce overall specimen size to save materials, due to the cost of the pre-sieved Ottawa sand.

The first task was completed using a regression analysis that compared how well the pullout force correlated to the transfer length of the accompanying pretensioned prisms. The summary of the Midwest sand and Ottawa sand regression analyses can be seen in Figure 4.10. The full results from both sets of this regression analysis can be found in Appendix C. From Figure 4.10 it is clear the Ottawa sand was overall a better predictor of measured transfer length.

Due to this fact, the Ottawa sand was selected to be used in further development of the wire bond test.

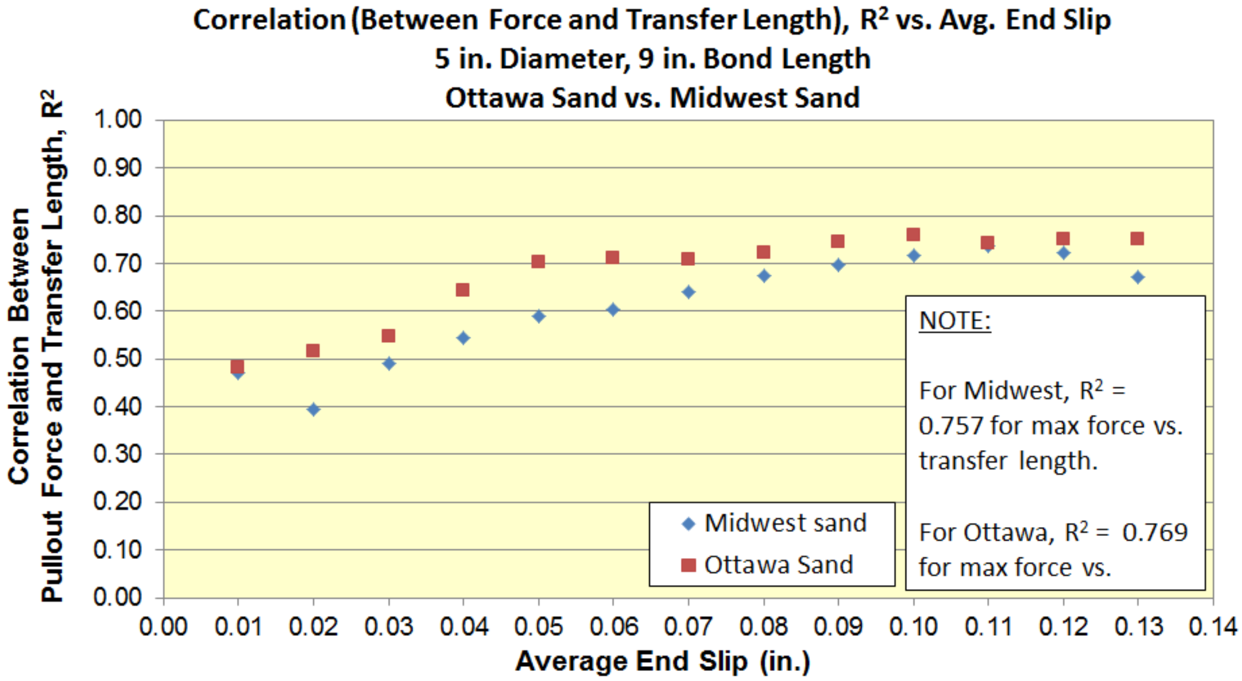


Figure 4.10 Ottawa vs. Midwest sand correlation to transfer lengths

To complete the second task, WF wire was selected because it exhibited the highest bond in specimens using both Midwest and Ottawa sand. The bond length was varied from 5 in., 7 in., and 9 in. All of these tests were performed in the 12-in. total length trial specimen cylinders. Twelve specimens – four each at 5-in., 7-in., and 9-in. bond lengths – were tested the same day, using the same batch of mortar in alternating fashion. Ottawa sand was used for these tests. Results of this test are shown in Figure 4.11. The 5-in. bond was the only specimen length that showed pullout failures and didn't have to be stopped for fear of rupturing the wires. However, it was noted the maximum pullout force for WF using a 5-in. bond length was only around 7300 pounds. Since WF had proven itself to be the upper limit of wires in this pullout testing program, the author wanted to make sure it remained close to the "rupture threshold" to keep the range of variation (allowable spread) among all wires as large as possible. To accomplish this, the author decided to try a 6-in. bond length moving to the next phase of developing the specimen size.

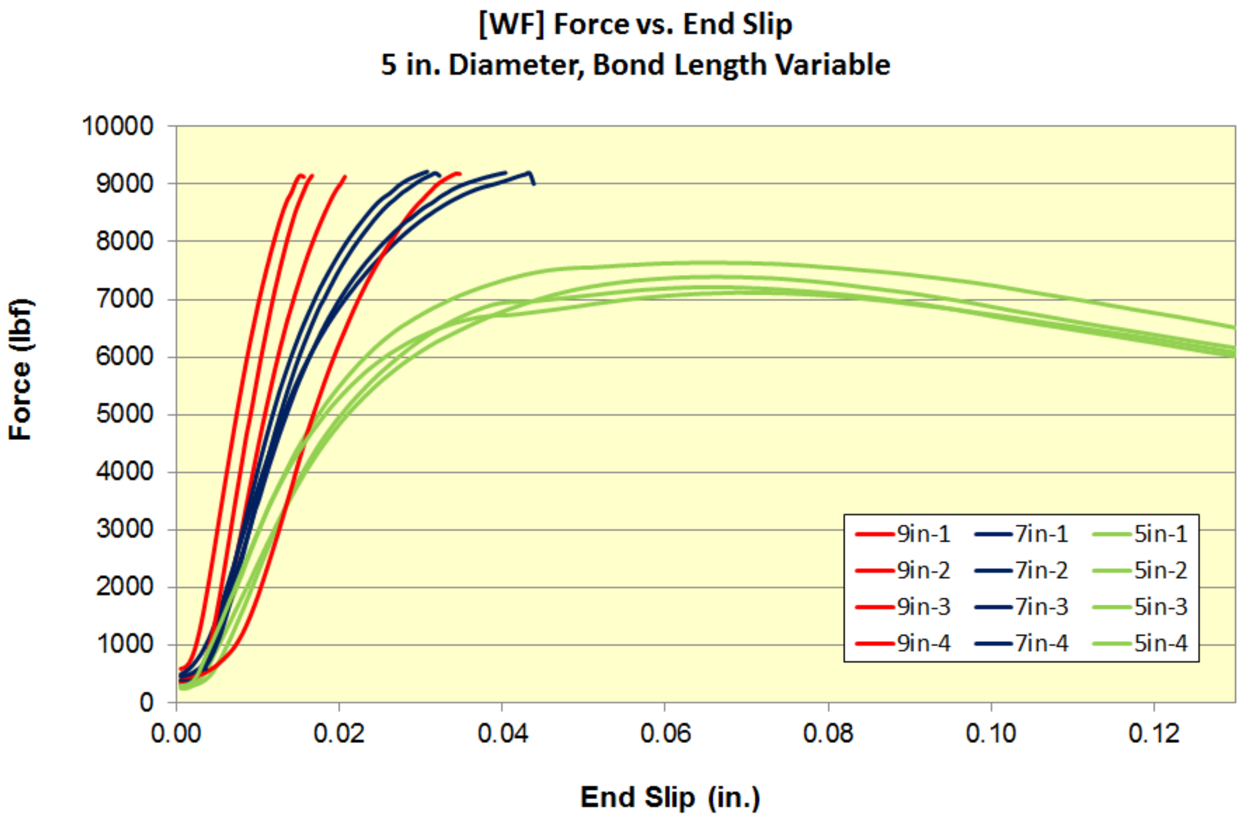


Figure 4.11 [WF] Variable bond length graph

The third goal of reducing the overall specimen size was accomplished by switching to a 4-in.-diameter tube with a total length of 8 in. Within the 8-in. long steel tube, there was a 6-in. embedment (bond) length with a 1-in.-long duct tape bond breaker at the bottom and a 1-in.-long duct tape bond breaker at the top. The top bond breaker extended past the top mortar surface by approximately 1 in. to ensure the exact bond length desired in case of settlement. The wire extended past the top mortar surface approximately 2 in.

By reducing the total length of the specimen from 12 in. to 8 in. and by switching from a 5-in.-diameter specimen to a 4-in.-diameter specimen, overall material costs were cut approximately 57.5%. This is important because, as was mentioned before, Ottawa sand costs approximately $1-1.20 per pound which is extremely expensive. Additionally, the 4”x8” specimen size is very common in concrete and mortar testing. This specimen size was verified to work and the results can be seen in Figure 4.13. Moving forward, the author anticipated this specimen size to yield a good differentiation between the highest bonding wires and lowest bonding wires. Final specimen dimensions can be seen in Figure 4.12.

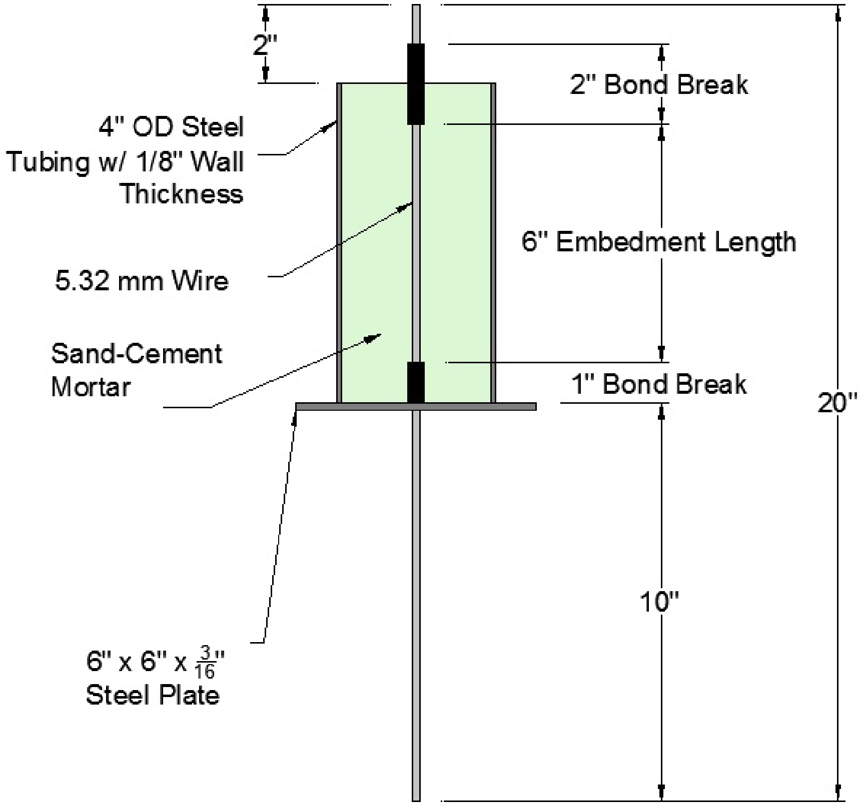


Figure 4.12 Final Specimen dimensions of wire pullout test specimen

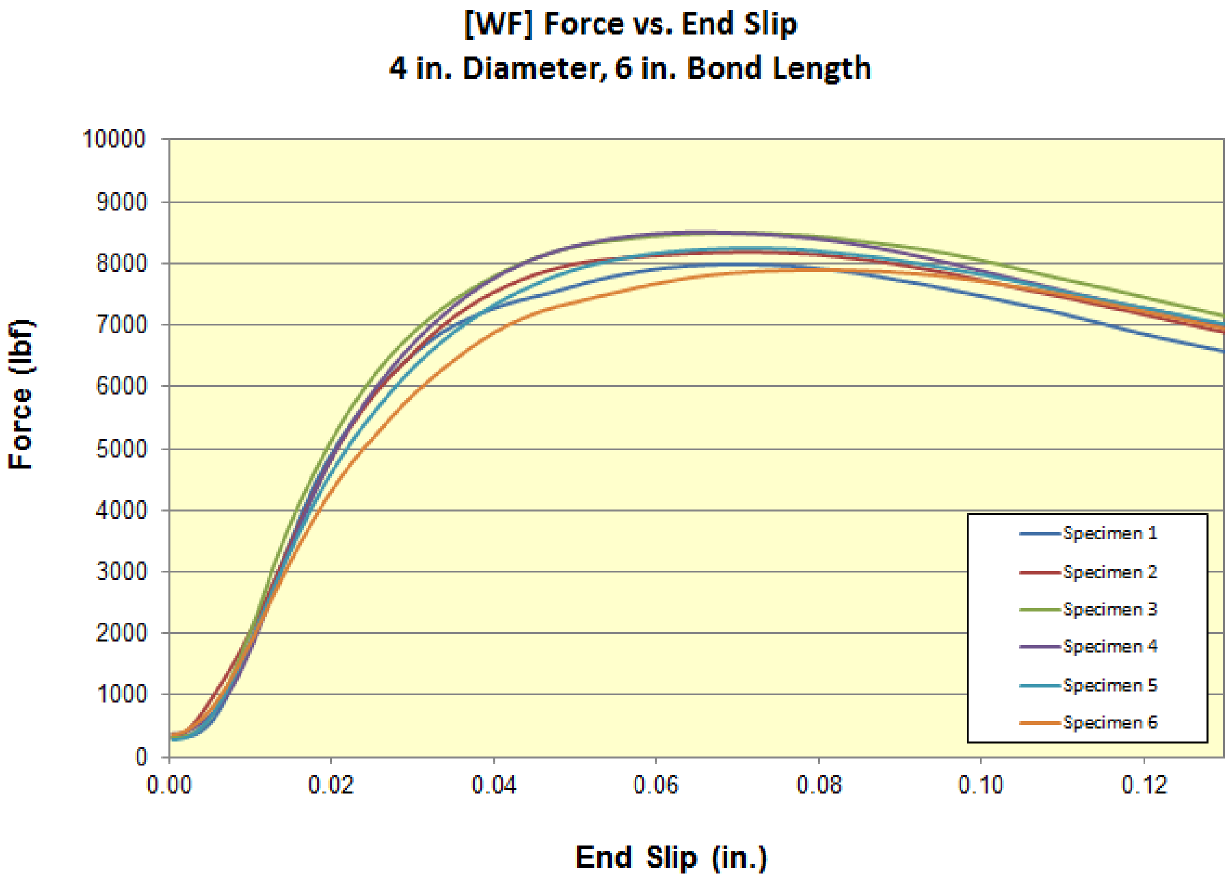


Figure 4.13 [WF] 4-in.-diameter specimen development, 6-in. bond length

4.2 Experimental Program

This section contains information used for this experimental testing program regarding development and verification of a standard pullout bond test for 5.32-mm-diameter steel prestressing wires. This information includes research variables; specimen dimensions; mix proportions, material sources, and match sizes; specimen casting and storage procedures; and testing procedures used to develop the un-tensioned pullout test.

4.2.1 Research Variables

Two primary research variables for the wire testing portion of the lab phase are indent geometry and surface condition. This is of great importance because it allows the researchers to better distinguish what portion of a reinforcement's bond performance can be attributed to indent geometry and what portion can be attributed to surface condition. These two effects were investigated by testing the reinforcements in both their “as-received” and “cleaned” conditions.

In total, 12 different wires with different indentation patterns from six different steel manufacturers were used to develop the un-tensioned pullout test described in detail in Chapter 4. All wires used were 5.32-mm-diameter, Grade 270, low-relaxation conforming to ASTM A881. The wires were stored at 25 foot lengths in PVC tubes with silica-based desiccant packets to prevent any rusting and preserve the wires’ “as-received” surface condition for testing.

First, indentation geometry of the steel prestressing wires was investigated by testing the wires with their “as-received” surface conditions. This allowed the relative bond performance of the wires to be examined and a baseline for expected bond performance to be established.

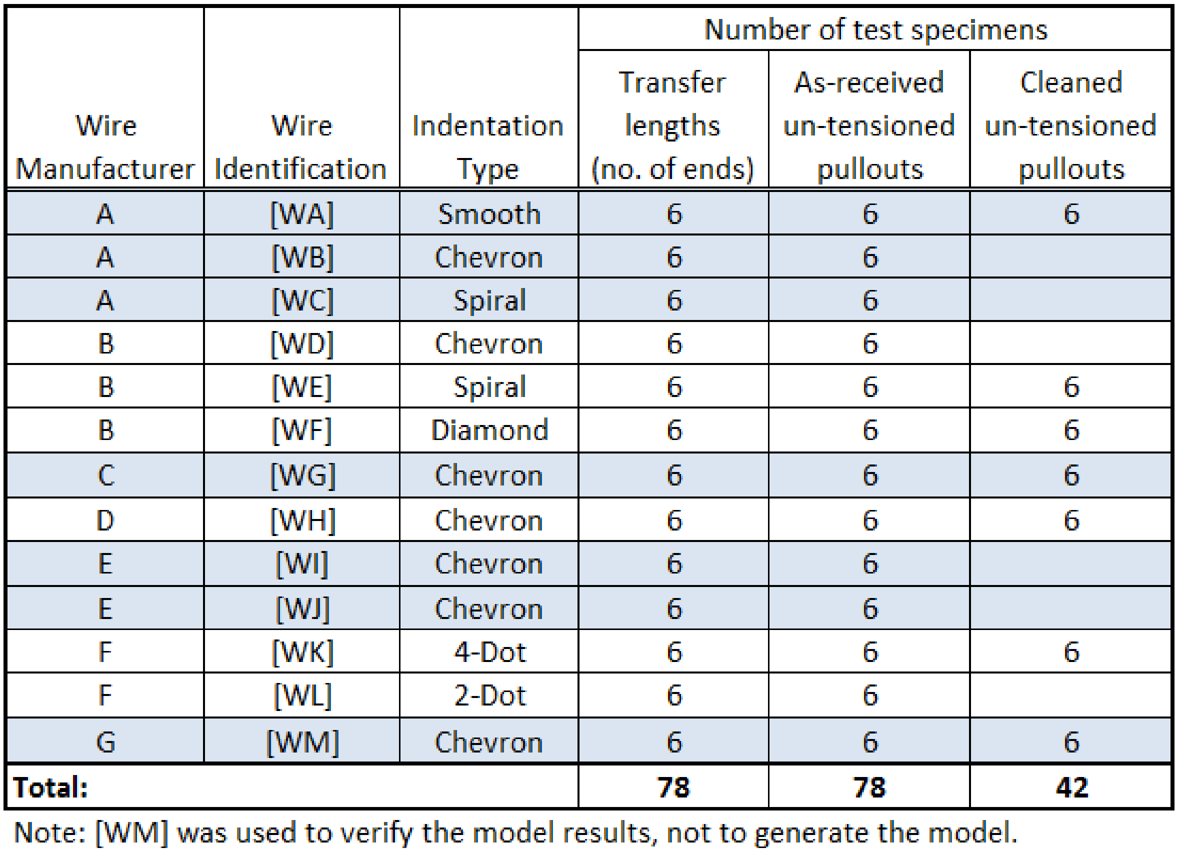
Second, surface condition of the wires was tested by cleaning the wires. This occurred by performing further pullout testing on six of the wires which had been subjected to the cleaning process described in depth in Section 3.3. The “cleaned” specimen tests were performed on bare steel by removing rust, oils, and surface lubricants with an acidic solution.

Results of these “cleaned” specimens were compared to the “as-received” specimens. This process allowed the researchers to better separate out the bond attributed to surface condition from the bond attributed to indent geometry.

The testing matrix for the wire pullout tests can be seen in Table 4.1. Each wire was tested six times and the results averaged to give the expected bond performance of each wire. Both the “as-received” and “cleaned” wire pullout results were compared to the measured transfer length of accompanying pre-tensioned prisms. These prisms were cast using a concrete mixture similar to one used in a major concrete tie manufacturing plant in the United States. The batching and testing procedures used to obtain the transfer lengths from these pre-tensioned prisms are presented in Bodapati’s 2013 paper, but are not discussed here.

The bond performance models generated by the “as-received” and “cleaned” pullout tests and accompanying pre-tensioned prisms were scrutinized using an additional, 13th wire, WM, from a seventh different steel manufacturer. This wire was not part of the test development phase. It was used to verify the testing procedure and determine how good the model was at predicting bond performance.

Table 4.1 Matrix of wire pullout testing program (lab phase)



Wire Manufacturer	Wire Identification	Indentation Type	Number of test specimens		
			Transfer lengths (no. of ends)	As-received un-tensioned pullouts	Cleaned un-tensioned pullouts
A	[WA]	Smooth	6	6	6
A	[WB]	Chevron	6	6	
A	[WC]	Spiral	6	6	
B	[WD]	Chevron	6	6	
B	[WE]	Spiral	6	6	6
B	[WF]	Diamond	6	6	6
C	[WG]	Chevron	6	6	6
D	[WH]	Chevron	6	6	6
E	[WI]	Chevron	6	6	
E	[WJ]	Chevron	6	6	
F	[WK]	4-Dot	6	6	6
F	[WL]	2-Dot	6	6	
G	[WM]	Chevron	6	6	6
Total:			**78**	**78**	**42**

Note: [WM] was used to verify the model results, not to generate the model.

4.2.2 Specimen Dimensions

The wire pullout specimens utilized a 4-in.-outer-diameter steel tube, 1/8-in. wall thickness, and a total length of 8 in. A 6-in. by 6-in. steel plate (3/16-in. thick) was tack welded to the bottom. The remaining contact surface between the tube and bottom plate was caulked to prevent any leakage. Within the 8-in. long steel tube, there was a 6-in. embedment (bond) length with a 1-in.-long duct tape bond breaker at the bottom and a 1-in.-long duct tape bond breaker at the top. The top bond breaker extended past the top mortar surface approximately 1 in. to ensure the exact bond length desired in case of settlement. The wire extended past the top mortar surface approximately 2 in. A schematic of the wire pullout specimen is shown in Figure 4.14. The bottom plate had a 1/4-in.-diameter hole drilled in the center to allow the steel wire to pass through. The wires were held centered in the tube using an additional fixture (shown in Figure 4.15) and rebar ties. The 4-in.-diameter steel tubes were able to be re-used by cutting the tack welds, removing the bottom plate, and pushing out the mortar (with a hydraulic actuator and specially-made frame).

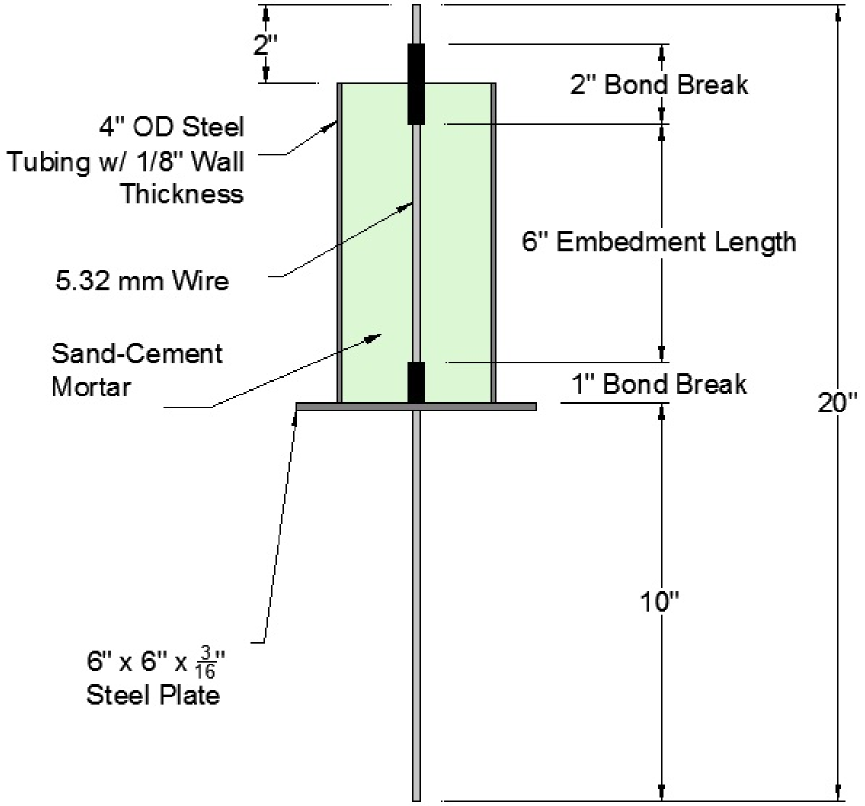


Figure 4.14 Final dimensions of wire pullout test specimen

Figure 4.15 Additional fixture used to center reinforcement during casting

4.2.3 Mix Proportions, Material Sources, and Batch Size

A sand-cement mortar mixture was used for all tests. The mix proportions were a water-to-cement ratio (w/c) of 0.427 and a sand-to-cement (s/c) ratio of 2.0. It should be noted the paddles of the pan mixer used for batching wire pullout specimens did not touch the bottom of the pan, causing some of the mortar to be unusable because of poor mixing action in this lower region. Due to this, the mix proportions will most likely vary at other testing locations. The cement used was a Type III cement from the Monarch Cement Company and it conformed to ASTM C150. The mill certification sheet for this cement can be seen in Appendix P. The sand used was supplied by Humboldt Manufacturing Co., Ottawa, Illinois. The sand was pre-sieved (conforming to ASTM C778) and arrived in 50-pound bags and boxes. Figure 4.16 shows the sand used for wire pullout tests.

Figure 4.16 Ottawa sand used for wire pullout specimens

For the as-received specimens, 1.0 ft^3 of mortar was batched. Each batch was enough to fill 12 wire specimens and 12 mortar cubes with approximately 15 pounds of mortar leftover. For the cleaned specimens, one cubic foot (1.45 ft^3) of mortar was batched. Each batch was enough to fill 18 wire specimens and 12 mortar cubes with approximately 15 pounds of mortar leftover. The mortar batch used for wire WM was the same as the as-received batch weights since 12 specimens were cast for this test – six as-received and six cleaned.

Total batch weights for the as-received and cleaned wire pullout tests can be seen in Table 4.2. Both the as-received and cleaned mortar batches had the same mix proportions (water-to-cement ratio and sand-to-cement ratio). The only difference was the total volume to accommodate either 18 specimens or 12 specimens. The pan mixer used can be seen in Figure 4.17.

Table 4.2 Batch weights used for wire pullout specimens

Material	As-Received Batch Weights (lbf)	Cleaned Batch Weights (lbf)
Ottawa Sand	81.1	114.4
Monarch Type III Cement	40.6	57.2
Water	17.3	24.4
Total	**139.0**	**196.0**

Figure 4.17 Pan mixer used for wire pullout tests

4.2.4 Specimen Casting and Curing Procedures

Each wire was tested six times and the results averaged. A total of six mortar batches were made with each batch containing 12 pullout specimens, one with each wire type. The specimens were cast in six different batches so that any variations due to slight differences in the mortar mixtures would be equally distributed. The mixer used for wire batches was a pan mixer with a maximum useable capacity of approximately 2.25 ft^3 and can be seen Figure 4.17.

Mortar for the wire pullout specimens used the following mixing procedure:

1. Place all of the sand and cement into the pan mixer and mix for one minute to combine.
2. Start timer while slowly add all of the water.
3. Mix for three minutes.
4. Turn off mixer. Scrape the mixer for two minutes using trowels, giving special attention to any area that collects dry material.
5. Mix for two minutes.

Each set of 12 pullout specimens were cast at approximately the same time each day, and the temperature in the vicinity of the curing location was maintained at 73.5 ± 3.5 ^oF in accordance with ASTM C109. Mortar temperature, room temperature, relative humidity, and mortar flow were recorded directly after the mortar came out of the mixer.

The flow table used for workability testing meets the specifications of ASTM C230 and the flow value is measured using the method ASTM C1437. A picture of the flow measurement process can be seen in Figure 4.18. Two-inch mortar cubes were made, stored, and tested according to ASTC C109. The pullout specimens were filled in two approximately equal lifts and consolidated using a wand-type vibrator between each lift.

After the specimens and mortar cubes were cast, the top surface of each pullout specimen was smoothed using a small trowel, and covered for storage (curing). The pullout test specimens and 2-in. mortar cubes were cured by placing a moist cloth over the top surface and covering with plastic. This kept the relative humidity of the specimens and cubes greater than or equal to 90%. The specimens and cubes were then stored in a temperature- and humidity-controlled room maintained at a temperature of 73.5 ± 3.5 ^oF and a relative humidity above 50%. Figure 4.19 shows a picture of the moist cloth/plastic covering method used for curing the cubes, and Figure 4.20 shows the curing method used for curing the specimens.

Figure 4.18 Mortar flow measurement

Figure 4.19 2-in. mortar cubes uncovered and covered

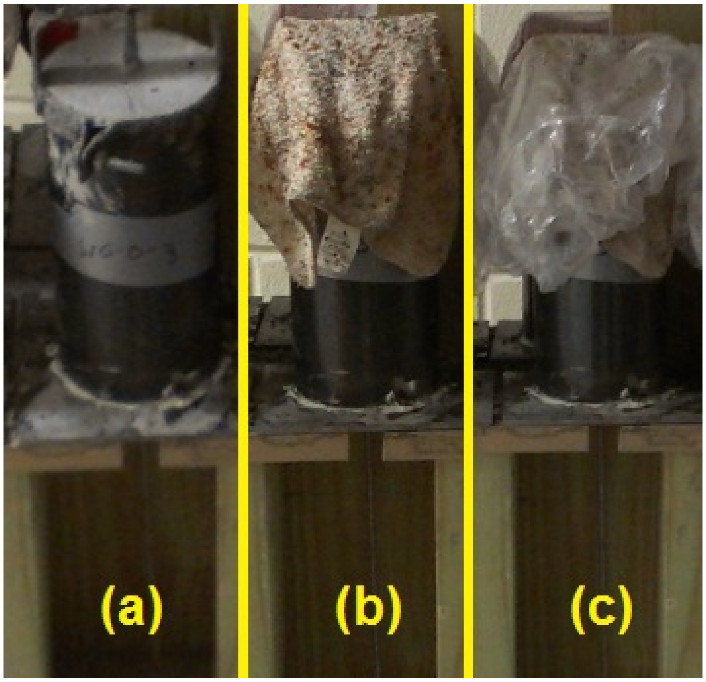


Figure 4.20 Specimen curing process used at KSU. Specimen is shown (a) after being finished with a trowel, (b) with the moist cloth on top, and (c) with the plastic cover to maintain the moist environment.

Average mortar strength at the time of wire pullout testing (measured from the mortar cubes) and mortar flow value are shown in Table 4.3 for the as-received wire specimens and Table 4.4 for the cleaned wire specimens. Individual cube strengths, flow, and temperature data can be found in Appendix D.

Table 4.3 As-received wire pullout batch summaries

Mortar Batch Name	Avg. Specimen Cure Time (hrs)	Avg. Cube Strength at Time of Test (psi)	Flow Value
Wire Batch #1	20.5	4544	124
Wire Batch #2	19.25	4638	124
Wire Batch #3	20.25	4541	122
Wire Batch #4	25.75	4544	125
Wire Batch #5	20.75	4542	121
Wire Batch #6	20.75	4640	119
Average of Six	**21.25**	**4575**	**122.5**
Wire Batch [WM]	21.5	4560	121

Table 4.4 Cleaned wire pullout batch summaries

Mortar Batch Name	Avg. Specimen Cure Time (hrs)	Avg. Cube Strength at Time of Test (psi)	Flow Value
Clean Wire Batch #1	17.5	4551	121
Clean Wire Batch #2	18.75	4605	123
Average of Two	**18.25**	**4578**	**122**
Wire Batch [WM]	21.5	4560	121

4.2.5 Testing Procedure

Pullout tests were performed shortly after the mortar cube strength reached 4500 psi and ended before the cube strength reached 5000 psi. During testing, the wires were pulled at a rate of 2000 lbs/minute at the bottom, while continuously monitoring and recording the applied load and free-end slip at the opposite (top) end using a linear variable differential transformer (LVDT). This process is shown in Figure 4.21. A 5.32-mm-diameter prestressing chuck was used for the actuator to bear and apply force to the wire. Since the same frame was used to test wires with a 5.32-mm diameter and strands up to 0.6-in. diameter, the pass-through hole of the pullout frame was notched at 0.75 in. The bearing surface of the wire chucks is smaller than 0.75 in., so a steel washer approximately 1.5-in.-outer diameter and 0.5-in. thick was fabricated for the wire chuck to bear on. A picture of this washer is shown in Figure 4.22.

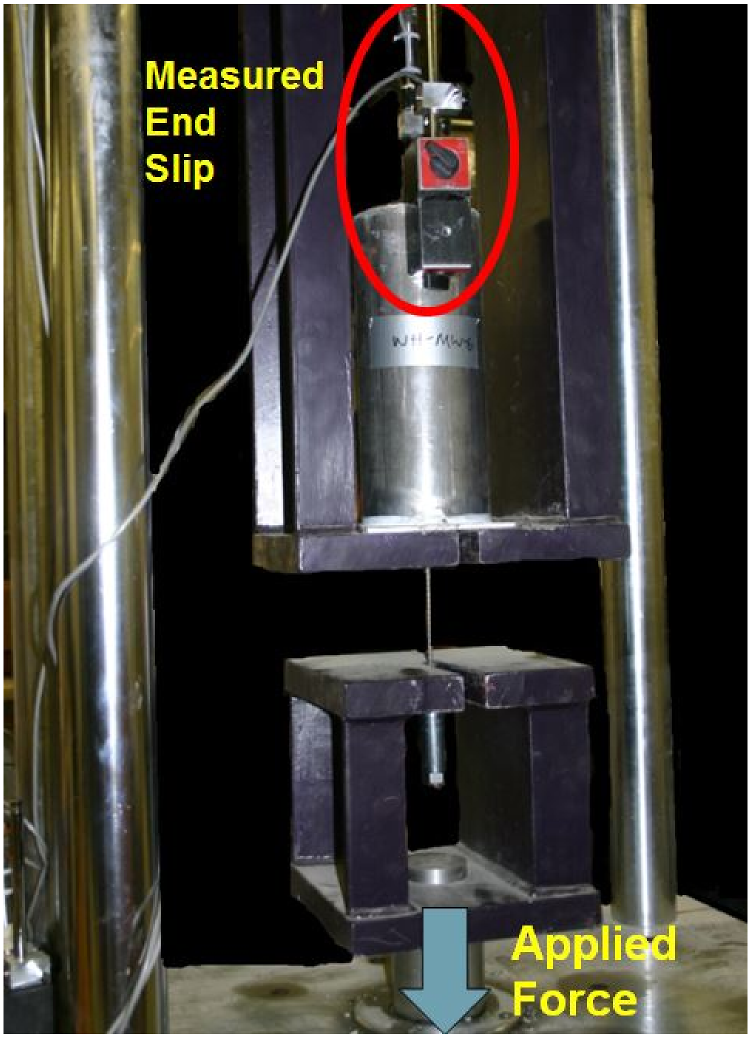


Figure 4.21 Pullout testing frame with specimen

Figure 4.22 Washer used for bearing of wire chuck

MTS MultiPurpose TestWare 793 software was used to control the servo-hydraulic actuator and also for data acquisition. A more in depth breakdown of the testing machinery setup and its specifications can be found in Section 4.2.6. A loading rate of 2000 lbs/min resulted in an average test length of about four to five minutes. This test length is similar to other ASTM test standards for concrete members, and will allow 12 or more pullout specimens to be tested in the allotted “strength window.” Data (time, force, and end slip) was collected at every 0.0005 in. of free-end slip using MTS software and hardware. The LVDT was positioned on the center of the free-end wire and was mounted to the steel can using two magnetic blocks. A closer view of the LVDT setup and top view of the wire specimen are shown in Figure 4.23.

Figure 4.23 LVDT and magnetic base setup

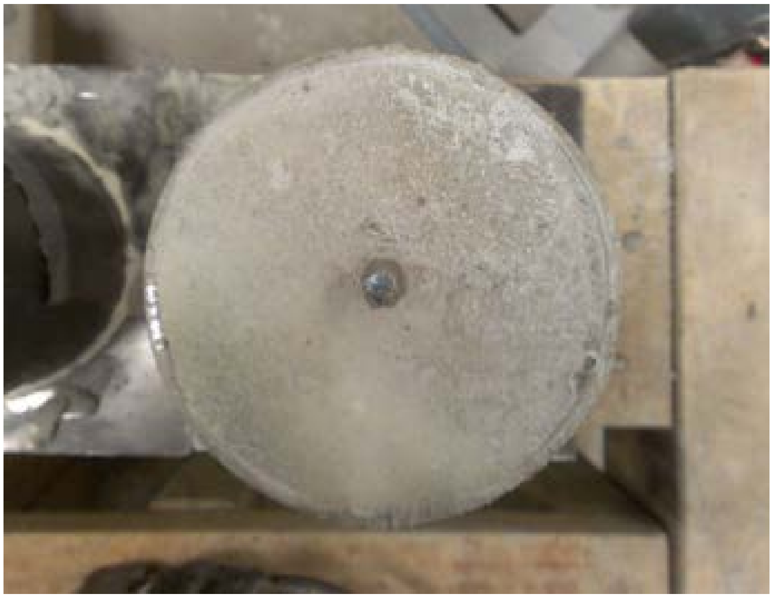


Figure 4.24 Top view of wire specimen

4.2.6 Testing Equipment

The following test setup was used for pullout testing. A silent-flow MTS hydraulic pump with a 30-gallon-per-minute (gpm) capacity – approximately 3000 psi – was used to run an MTS Flex Test GT controller. However, the servo valves have a maximum flow of 15 gallons per minute (gpm). MTS MultiPurpose TestWare 793 software was used to control the servo-hydraulic actuator and also for data acquisition. This actuator was connected to the bottom section of the pullout load frame. The top section of the pullout load frame was connected to a load transducer. This load transducer has a maximum capacity of 100,000 pounds, but the system was calibrated to a 10,000 pound range for wire testing and a 40,000 pound range for strand testing. Pullout force, end slip, actuator position and time data were recorded every 0.0005 in. of free end slip using a linear variable differential transformer (LVDT).

A schematic of the pullout load frame at Kansas State University (KSU) used for pullout testing is shown in Figure 4.25. This frame is nearly identical to the frame used to develop the Standard Test for Strand Bond (Ramirez and Russell, 2008).

A Forney testing machine with a 250,000-pound capacity was used to test the strength of the mortar cubes. This machine can be seen in Figure 4.26. A rolling cart was built for the transportation and casting of pullout specimens and mortar cube molds. A picture of this cart can be seen in Figure 4.27.

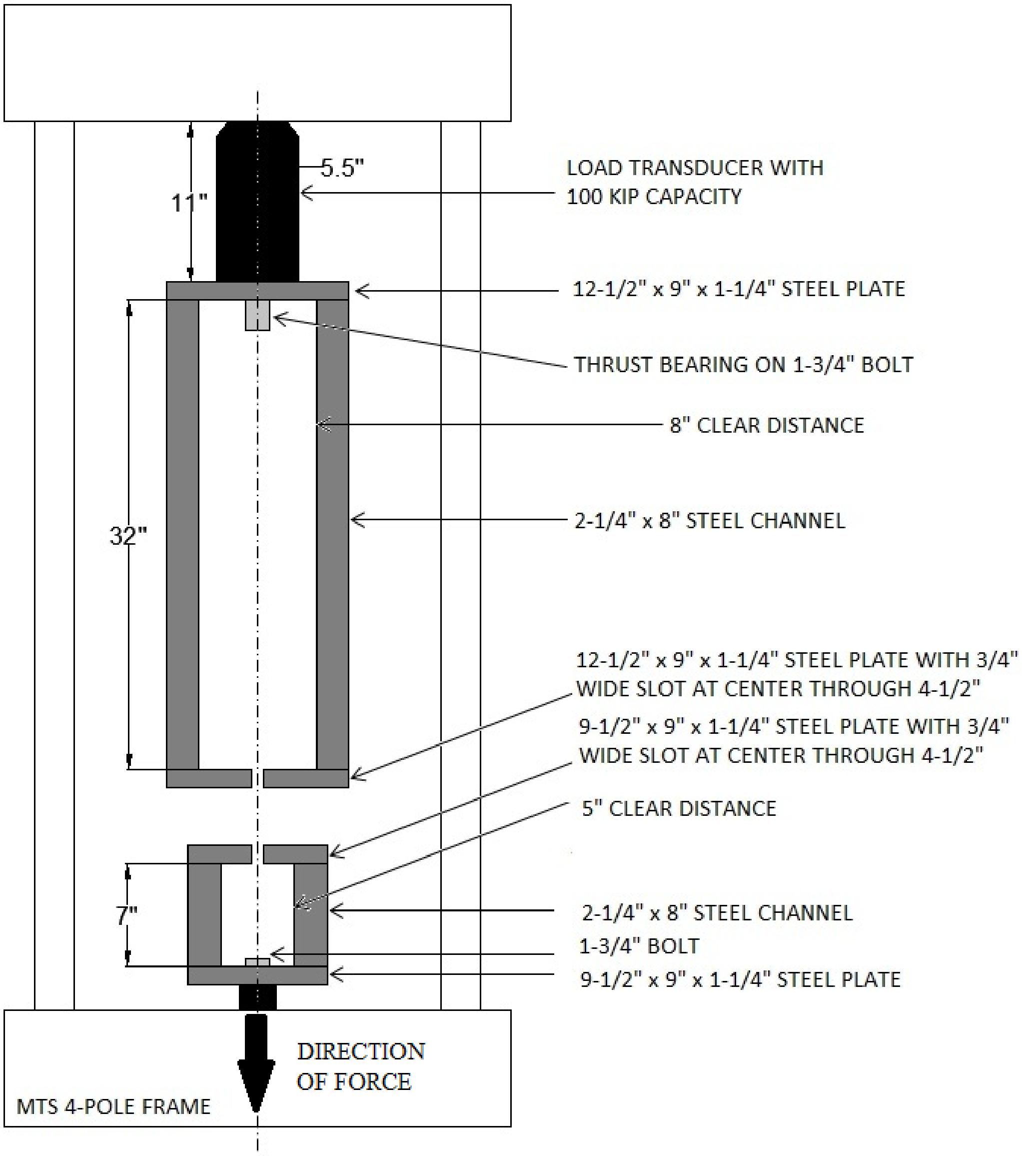


Figure 4.25 Schematic of pullout load frame at Kansas State University

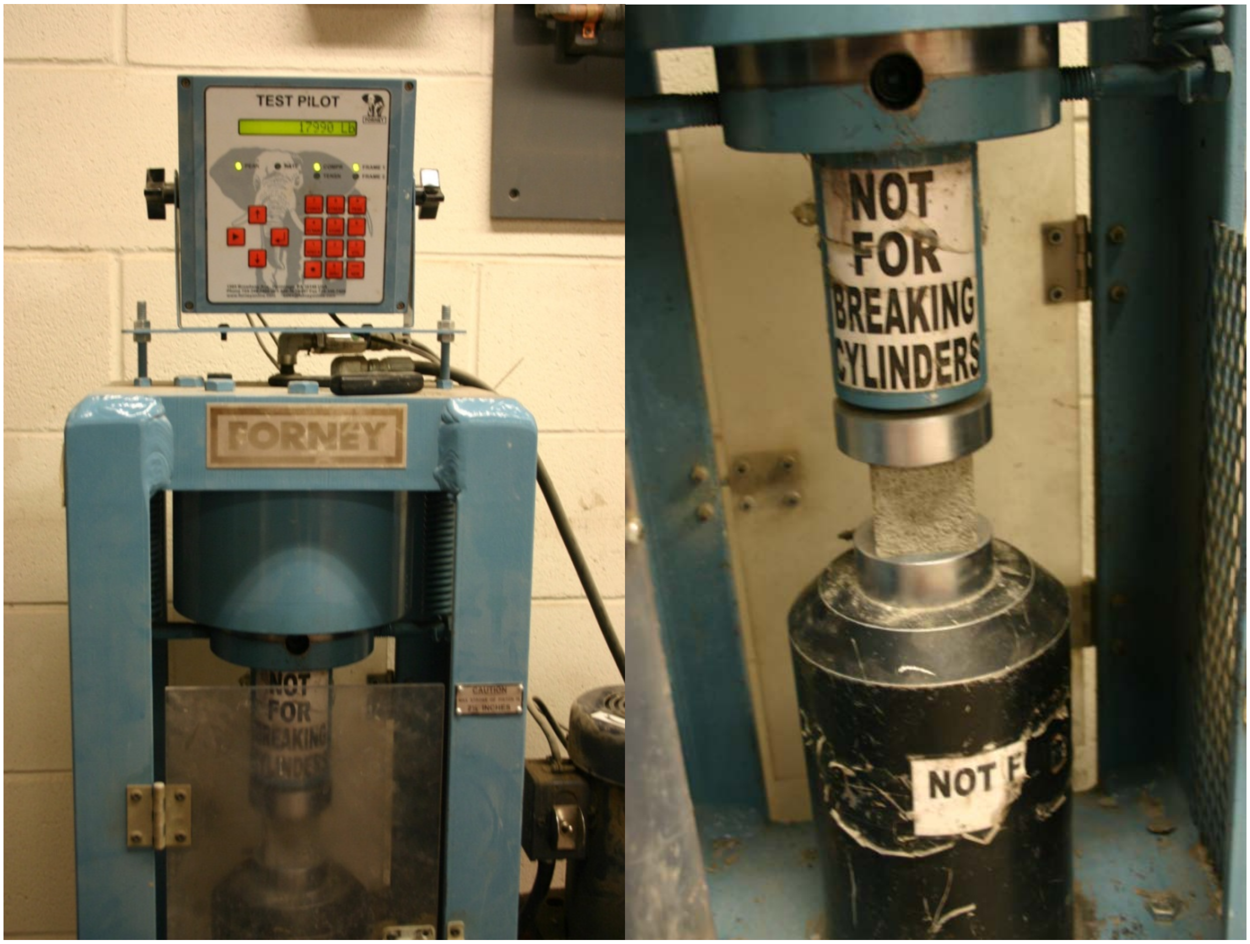


Figure 4.26 Forney testing machine used for testing mortar cube strength

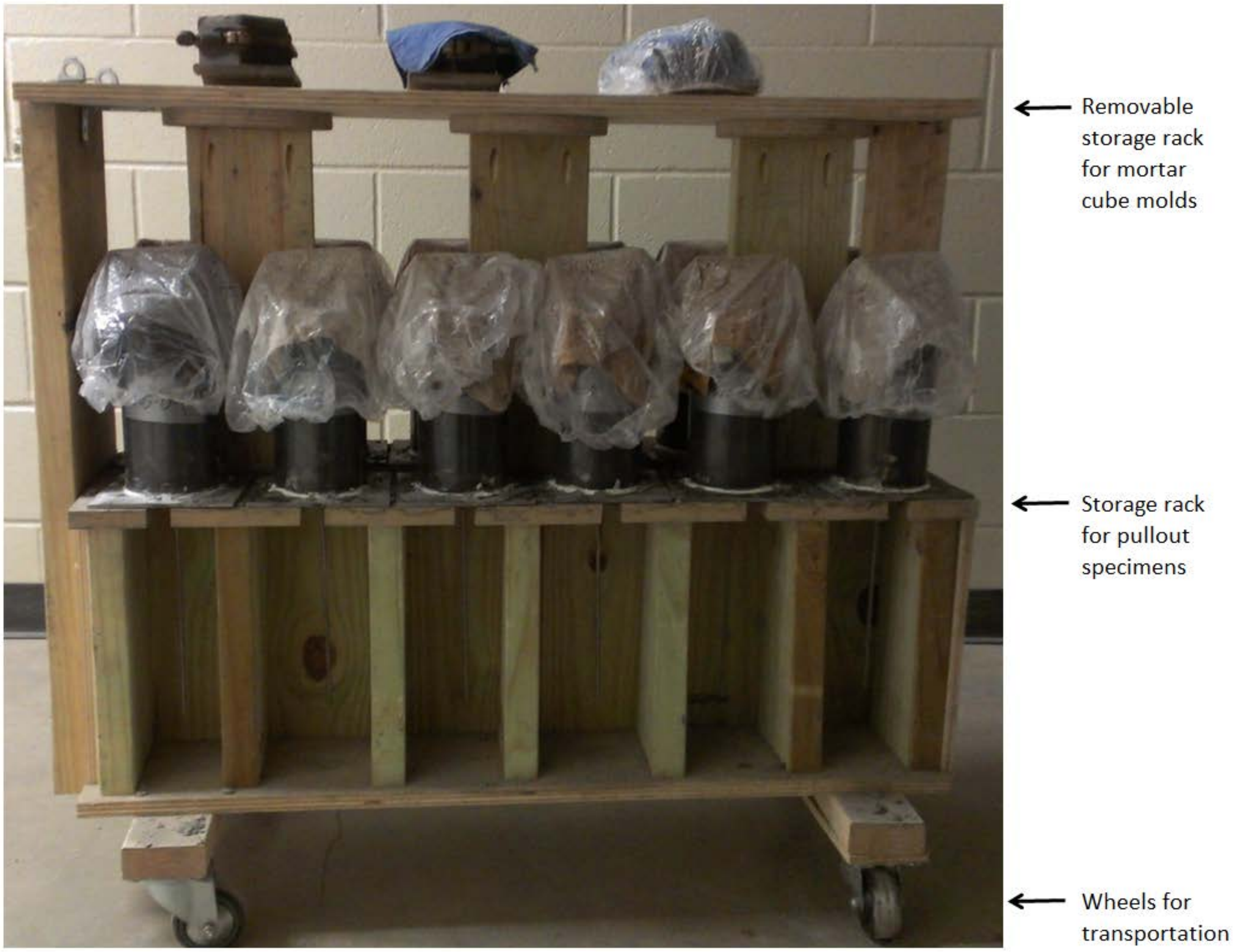


Figure 4.27 Specimen transportation cart

4.3 Wire Pullout Results and Analysis

Results of the experimental, lab wire testing program are presented in this section. First, results of the “as-received” and “cleaned” pullout specimens are presented in succession. The third section presents transfer length measurements obtained from pre-tensioned prisms. Next, the best method of analysis to be used for wire bond testing is established from multiple methods. The fifth and sixth sub-sections aim to verify the predictive nature of both models (as-received and cleaned) using the final wire WM. Finally, results between the as-received data set and cleaned data set are compared to distinguish between bond attributed to surface condition and bond attributed to indent geometry.

4.3.1 As-Received Results

The averaged as-received force vs. end slip results from each wire source is presented in Figure 4.28. The average force at each increment of end slip (0.0005 in.) was obtained by arithmetically adding the force results from each of the six individual specimens and then dividing by six. The same process was used to average the end slip measurements for each wire group.

Each line on the graph represents the average of six individual specimens from the same wire source. Each of the six specimens was cast in a different batch of mortar with the same mix design except for WM. All six WM specimens were cast in the same batch of mortar at a later date to be used to verify the as-received model. Force vs. end slip graphs showing individual results of the six specimens for each wire source can be seen in Appendix E.

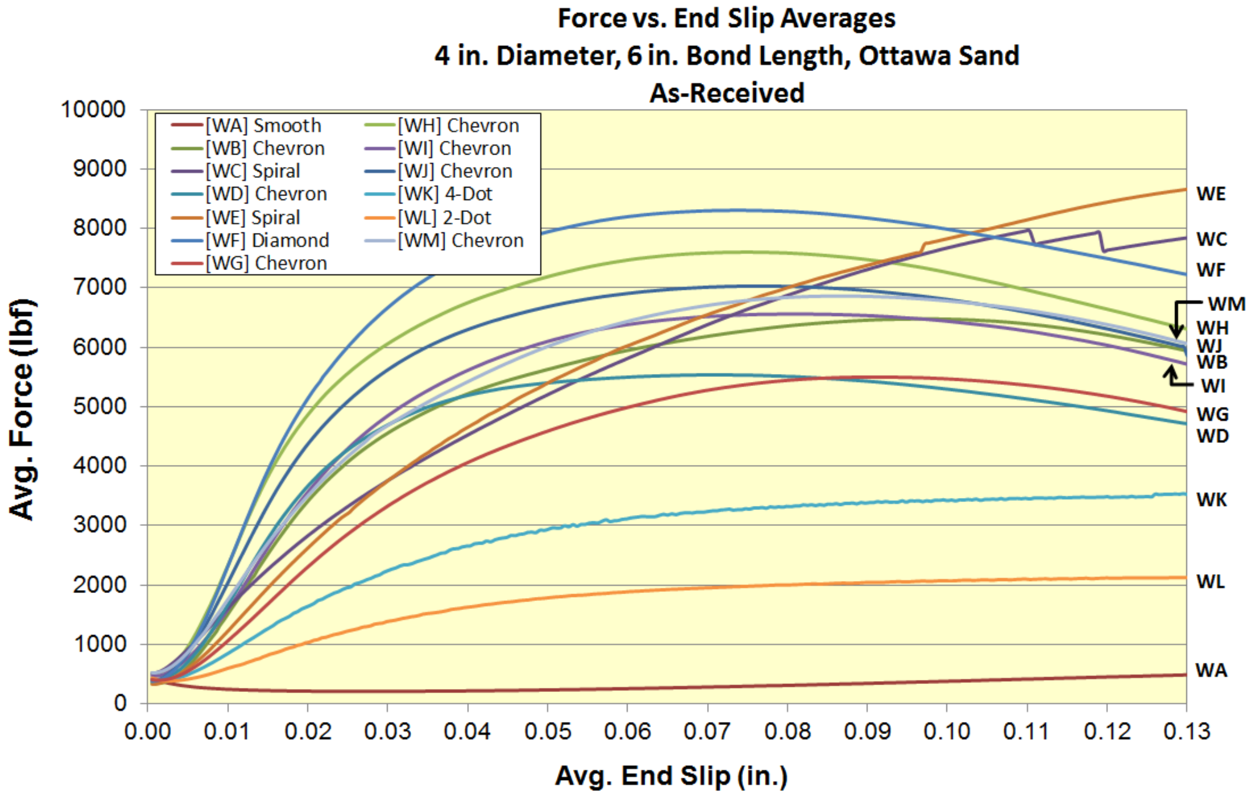


Figure 4.28 As-received wires, force vs. end slip averages

4.3.2 Cleaned Results

The averaged cleaned results from each wire source are presented in Figure 4.29. The average force at each increment of end slip (0.0005 in.) was obtained by arithmetically adding the force results from each of the six individual specimens and then dividing by six. The same process was used to average the end slip measurements for each wire group.

Each line on the graph represents the average of six individual specimens from the same wire source. Two batches of mortar with the same mix design were made for the cleaned results. Each batch of mortar contained three specimens of each wire source except for WM. All six WM specimens were cast in the same batch of mortar at a later date to be used to verify the cleaned model. Graphs showing individual results of the six specimens for each wire source can be seen in Appendix E. The wires were cleaned according to the procedure described in Section 3.3.

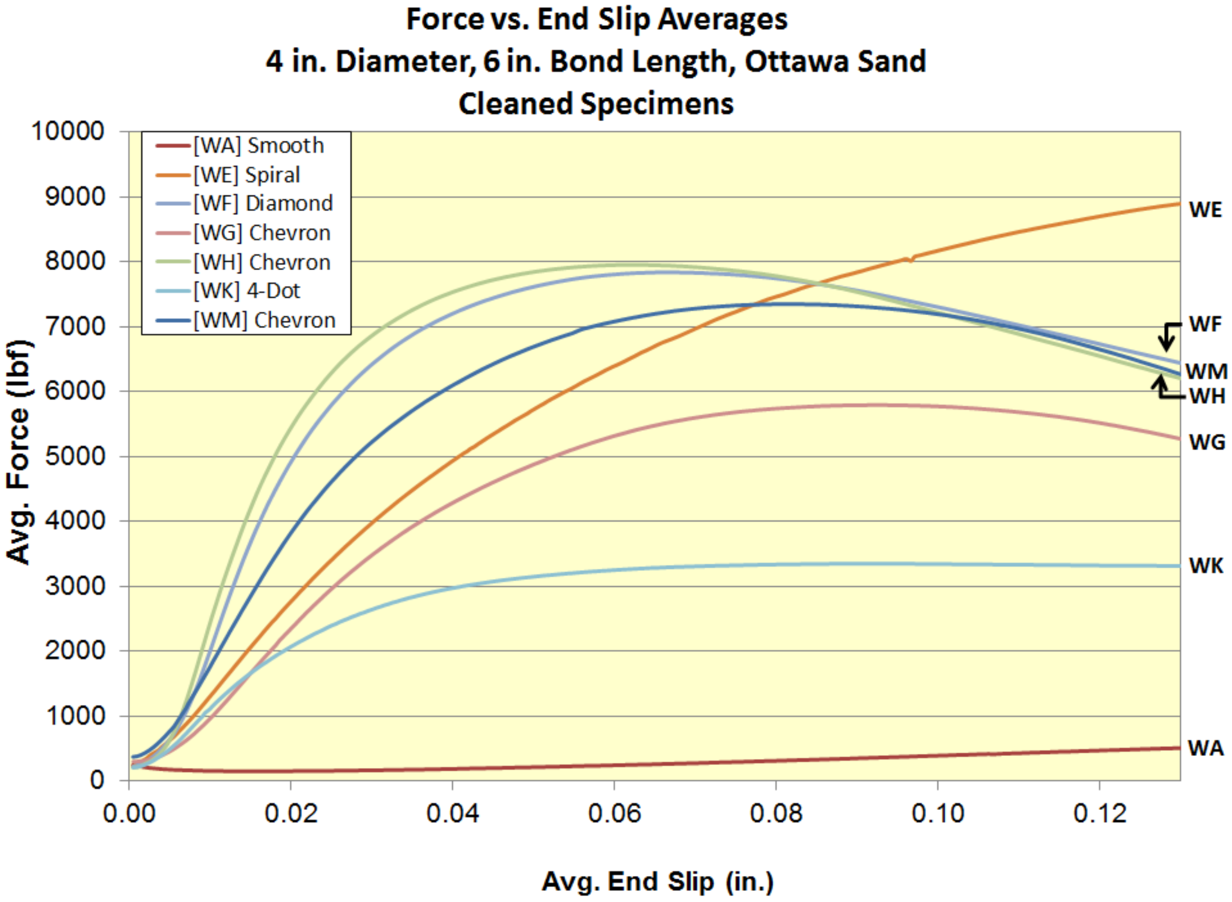


Figure 4.29 Cleaned wires, force vs. end slip averages

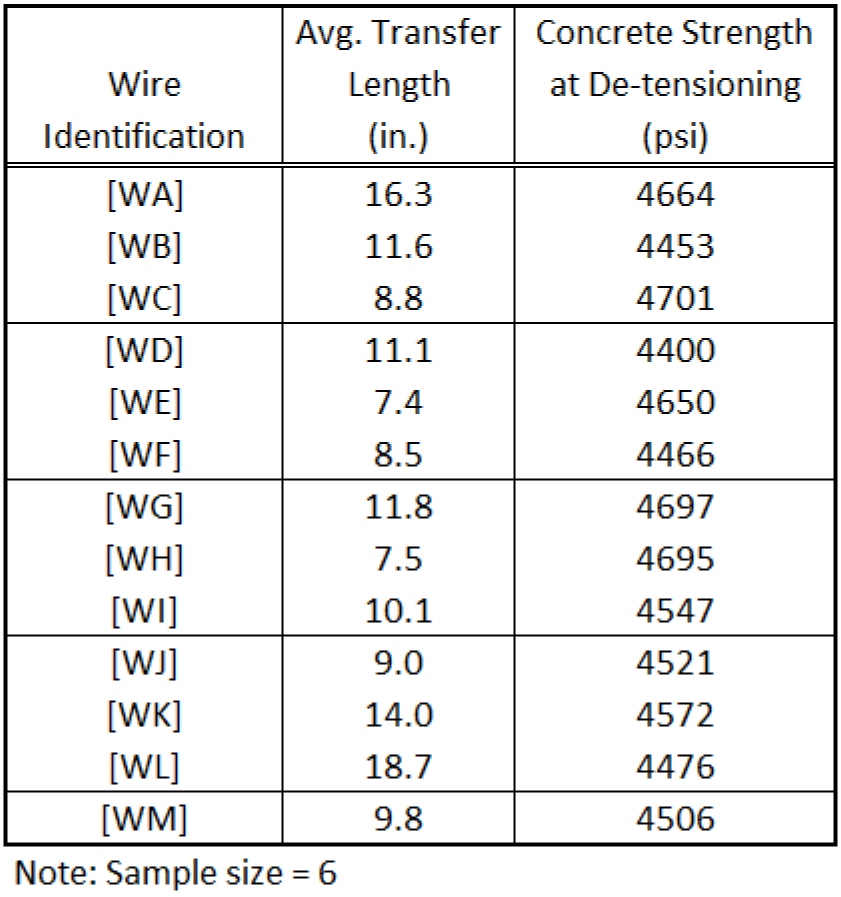
4.3.3 Transfer Length Data

Data presented in Table 4.5 shows the average wire transfer length measurements determined from the surface strain data obtained by the KSU research team. Transfer lengths were determined from the surface strain data obtained from accompanying pre-tensioned prisms using the same wires as the pullout tests. Surface strain data was obtained for the entire length of the prisms. A bilinear strain profile was assumed for the software that calculated the transfer lengths.

The wires used for the pre-tensioned prisms were stored and preserved along with the wires used for the pullout tests. Three pre-tensioned prisms were cast using each wire. A transfer length was measured from each member end, resulting in a total of six transfer lengths (six data points).

Prisms were cast with four wires in a square pattern and were meant to be as representative as possible of actual concrete railroad ties. The concrete-to-steel-wire area of each prism is approximately the same as that of a typical concrete railroad tie produced in the United States. Additionally, the prisms were cast using a concrete mixture similar to one used in a major concrete tie manufacturing plant in the United States. This mixture utilized the same coarse aggregate sources, mix proportions, and admixtures as the manufacturing plant. The prisms were de-tensioned at approximately 4500 psi (the same strength of the mortar used for pullout testing). Actual strength of the concrete at the time of de-tensioning for each batch is listed in Table 4.5. The batching and testing procedures used to obtain the transfer lengths from these pre-tensioned prisms are presented in Bodapati’s 2013 paper, but are not discussed here.

Table 4.5 Wire transfer length data



Wire Identification	Avg. Transfer Length (in.)	Concrete Strength at De-tensioning (psi)
[WA]	16.3	4664
[WB]	11.6	4453
[WC]	8.8	4701
[WD]	11.1	4400
[WE]	7.4	4650
[WF]	8.5	4466
[WG]	11.8	4697
[WH]	7.5	4695
[WI]	10.1	4547
[WJ]	9.0	4521
[WK]	14.0	4572
[WL]	18.7	4476
[WM]	9.8	4506

Note: Sample size = 6

4.3.4 Selecting the Method of Analysis

All methods of analysis in this section compared results from Section 4.3.1 (as-received wire pullout data) to results from Section 4.3.3 (wire transfer length data).

Data from the wire pullout specimens were analyzed using four different methods:

1. Average pullout force at certain free-end slips
2. Free-end slip at certain average pullout forces
3. Slope between certain free-end slip values (0.01 to 0.03 in.)
4. Slope between a certain force values (1000 to 4000 lbf)

4.3.4.1 Average Pullout Force at Certain Free-End Slips

The first method of analysis consisted of looking at what force was required to cause a certain amount of end slip. The standard test for strand bond, ASTM A1081, states the result of the test should be reported as the pullout force at 0.10 in. of end slip. From the NASP Round 2 testing (Russell and Paulsgrove, 1999b), the most reproducible results between multiple testing sites was found at a force occurring at 0.10 in. of end slip.

Researchers of this experimental program wanted to determine if the pullout force at 0.10 in. of free-end slip provided the best correlation when compared with the measured transfer lengths, or if better correlation could be achieved using another point of end slip. To accomplish this goal, average pullout force at certain end slips was compared to the average transfer lengths. The force was analyzed for end slips ranging from 0.01 in. to 0.13 in. in increments of 0.01 in. of end slip for all 12 wires. Additionally, the maximum force occurring at any location less than or equal to 0.10 in. of end slip was also compared with the transfer length data. This limit of 0.10 in. was set because these tests were conducted in force-control, and since several of the wires had force values that were on the descending portion of the force vs. end slip graphs.

The coefficient of determination (R^2) between pullout force and transfer length was calculated for each of the data sets described in the previous paragraph. For brevity, a select few of these results are shown in the main body of this report. Results of the force at 0.10 in. of end slip compared with the transfer length can be seen in Table 4.6 and Figure 4.30. Results of the maximum force less than or equal to 0.10 in. of end slip compared with the transfer length can be seen in Table 4.7 and Figure 4.31. The entire set of results of pullout force at end slips ranging from 0.01 in. to 0.13 in. in increments of 0.01 in. of end slip can be seen in Appendix F.

For clarification: the x-coordinate (abscissa) of each point in these graphs represents the average of six transfer length readings; the y-coordinate (ordinate) of each point in these graphs represents the average of six pullout forces required to cause the indicated end slips. The R^2 is the correlation between these two averaged data sets.

Additionally, the data was re-analyzed for the set including only wires with non-continuous indentations. This was done because the smooth and spiral wires exhibit a different slip pattern than the individually-indented wires, and the researchers wanted to see whether or not a good correlation could be achieved for wires with non-continuous indentations. This brought the total number of wires (data points) down to nine for all data sets discussed above.

Results of the “force at 0.10 in. end slip” can be seen in Table 4.6 and Figure 4.32. Results of the “max force less than or equal to 0.10 in. end slip” can be seen in Table 4.7 and Figure 4.33. The entire set of results of pullout force at end slips ranging from 0.01 in. to 0.13 in. in increments of 0.01 in. of end slip with the smooth and spiral wires excluded can be seen in Appendix F.

Results of the regression analysis for all 12 wires and for nine wires (wires with non-continuous indents only) are summarized in Table 4.8 and Figure 4.34. The correlation between average pullout force and average transfer length (R^2) is plotted at each increment of end slip. Please note the R^2 value consistently trends upward and then starts decreasing, again in a consistent manner. This trend occurs for both 12-wire and nine-wire data sets and indicates reliable results.

For the 12-wire data set, pullout forces recorded at 0.10 in. of end slip provide the best correlation to transfer lengths when the forces were taken at a certain end slip. However, slightly better correlation was achieved when the maximum pullout forces recorded less than or equal to an end slip of 0.10 in. was used. For the nine-wire data set, the pullout force at 0.06-in. end slip, 0.07-in. end slip, and the maximum pullout force (ES ≤ 0.10 in.) had nearly identical R^2 values of 0.920, 0.920, and 0.916, respectively.

When considering both data sets, it can be seen that using the maximum pullout force at any location less than or equal to 0.10 in. end slip provides the best correlation to measured transfer length when using this method of analysis (force at an end slip). For the data set including all 12 wires, an $R^2 = 0.882$ is the best correlation achieved. For the data set excluding the smooth and spiral wires (nine wires included), an $R^2 = 0.916$ was the best correlation achieved.

Table 4.6 As-received wires, pullout force at 0.10 in. end slip

As-Received Pullout Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
Pullout Force at 0.10 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	378	32	8.5	16.3
[WB]	6473	563	8.7	11.6
[WC]	7663	969	12.6	8.8
[WD]	5302	300	5.7	11.1
[WE]	7817	487	6.2	7.4
[WF]	7993	441	5.5	8.5
[WG]	5469	388	7.1	11.8
[WH]	7270	462	6.4	7.5
[WI]	6439	498	7.7	10.1
[WJ]	6814	591	8.7	9.0
[WK]	3434	347	10.1	14.0
[WL]	2067	323	15.6	18.7

Note: Sample Size = 6, WE = 5

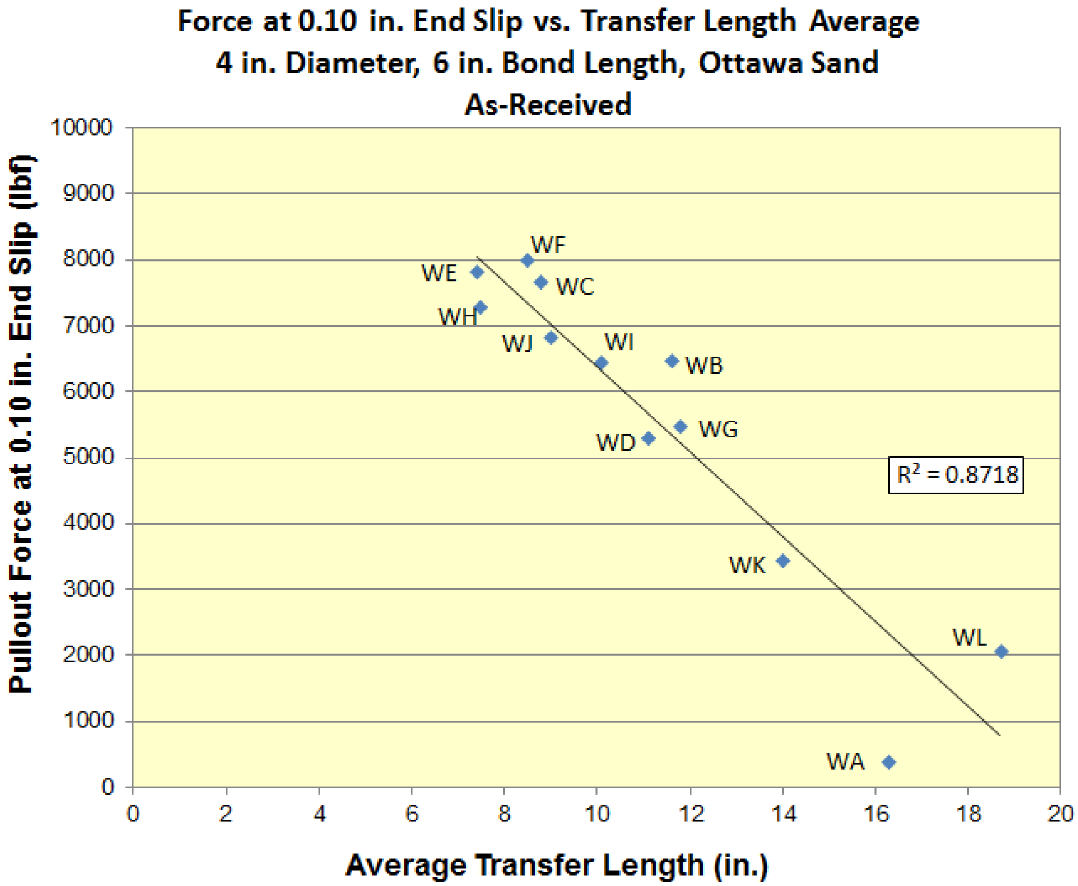


Figure 4.30 As-received wires, pullout force at 0.10 in. end slip

Table 4.7 As-received wires, maximum pullout force

As-Received Pullout Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Maximum Pullout Force				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	487	42	8.7	16.3
[WB]	6481	570	8.8	11.6
[WC]	7646	967	12.6	8.8
[WD]	5555	357	6.4	11.1
[WE]	7674	526	6.9	7.4
[WF]	8312	459	5.5	8.5
[WG]	5505	385	7.0	11.8
[WH]	7605	497	6.5	7.5
[WI]	6567	522	8.0	10.1
[WJ]	7034	635	9.0	9.0
[WK]	3447	354	10.3	14.0
[WL]	2068	322	15.6	18.7

Note: Sample Size = 6

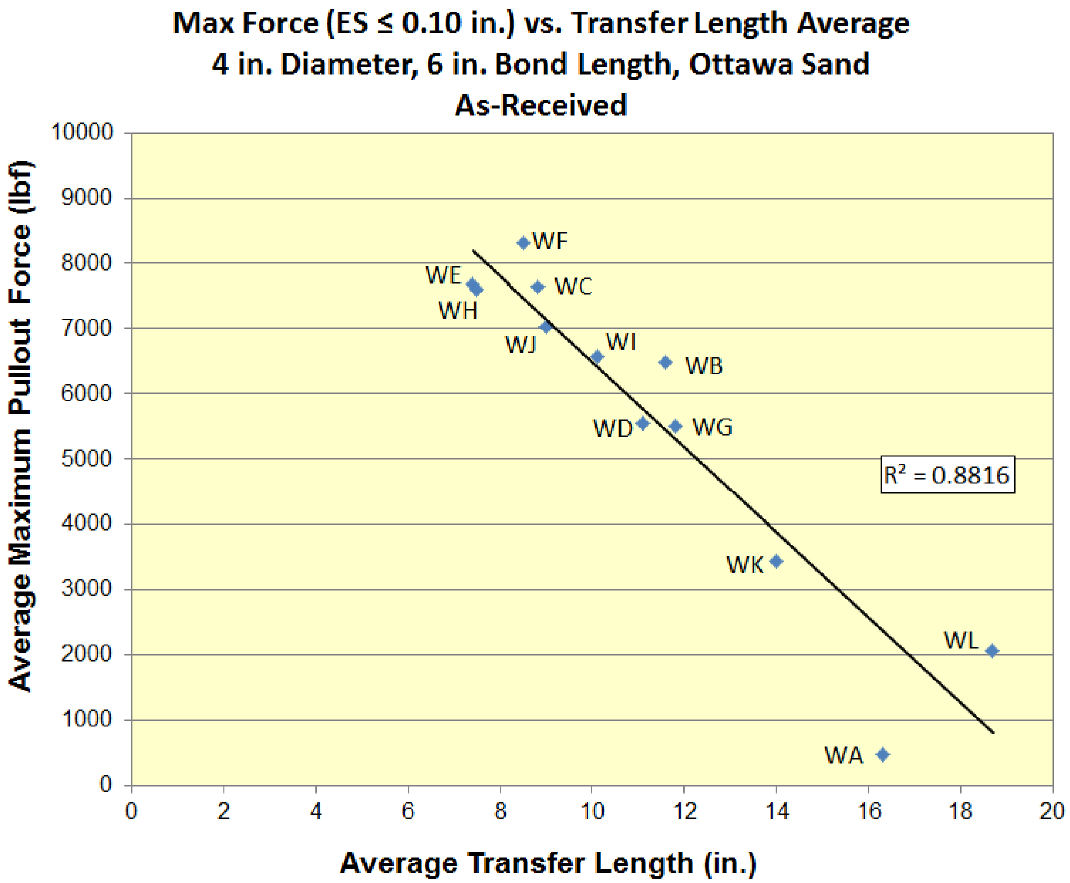


Figure 4.31 As-received wires, maximum pullout force

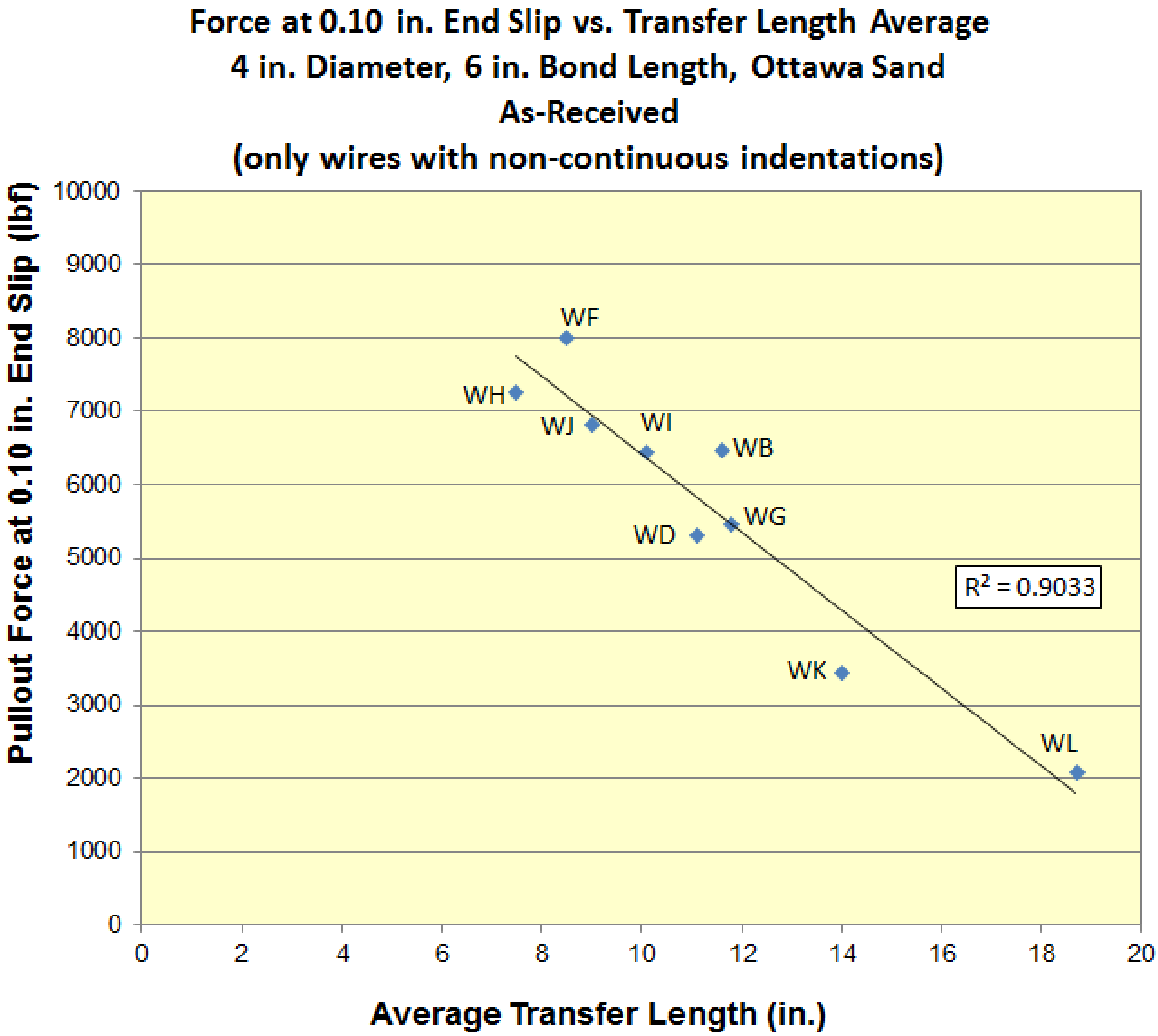


Figure 4.32 As-received wires, pullout force at 0.10 in. end slip (individual-indents only)

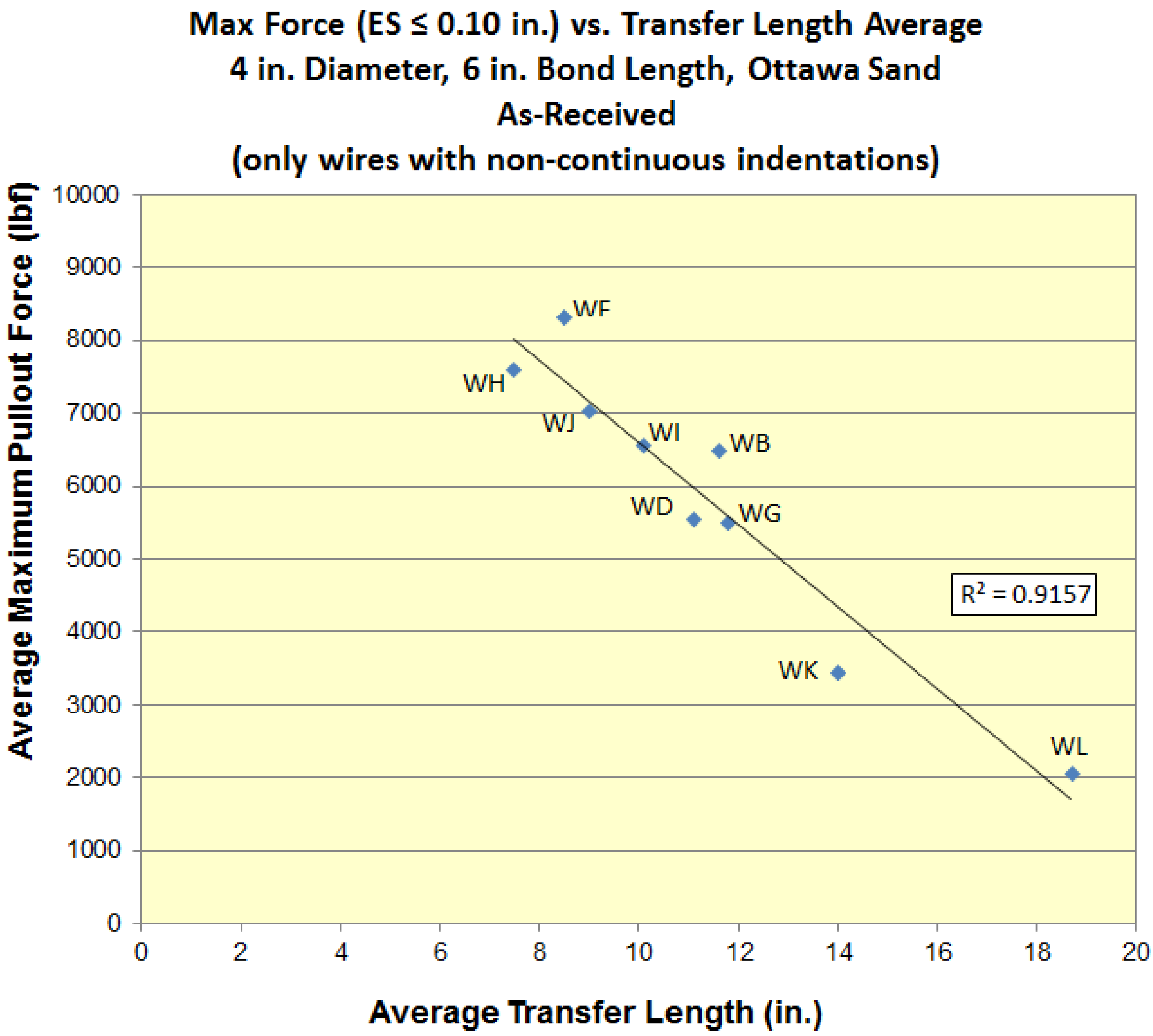
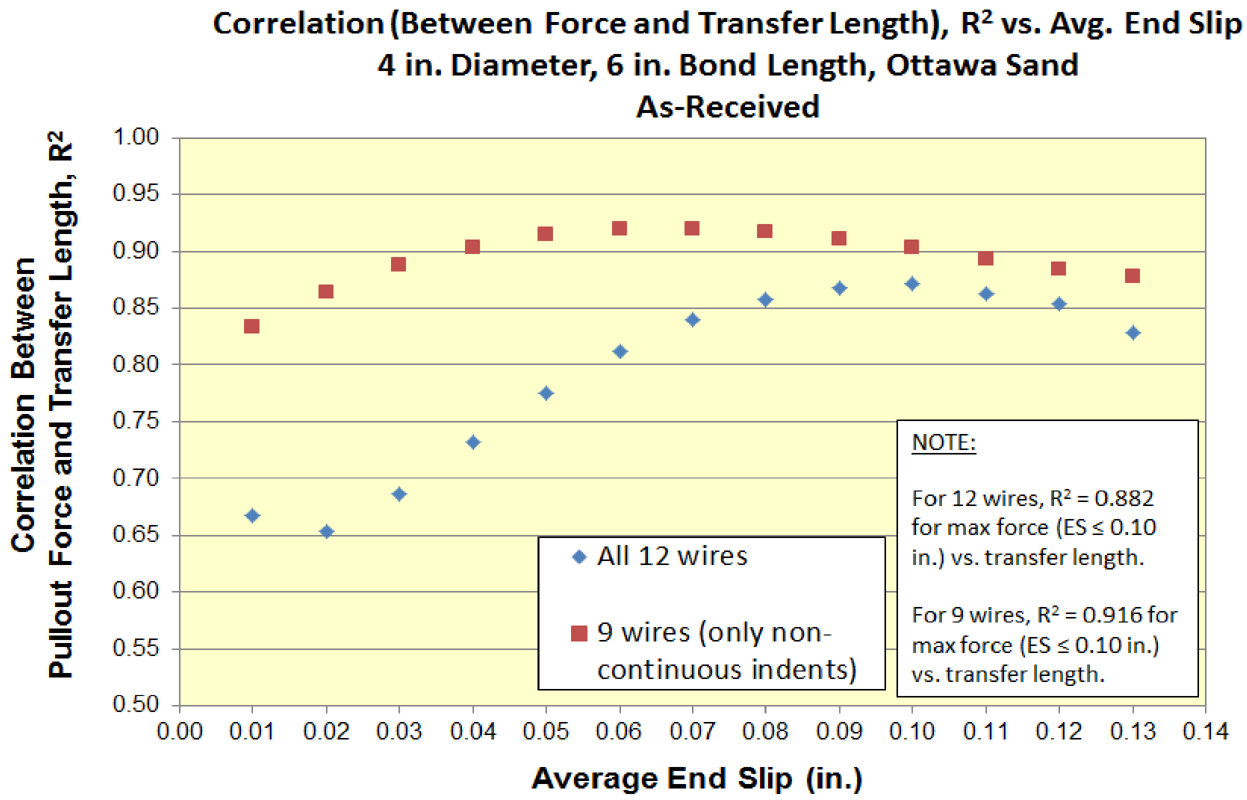


Figure 4.33 As-received wires, maximum pullout force (individual-indents only)

Table 4.8 As-received wire regression summary, force at an end slip

End Slip (in.)	R^2	
	All 12 wires	9 wires (individual-indents only)
0.01	0.668	0.834
0.02	0.653	0.864
0.03	0.686	0.888
0.04	0.732	0.904
0.05	0.776	0.915
0.06	0.812	0.920
0.07	0.839	0.920
0.08	0.858	0.917
0.09	0.868	0.910
0.10	0.872	0.903
0.11	0.862	0.893
0.12	0.853	0.884
0.13	0.828	0.878
Max Force	0.882	0.916
Highest R^2 of set	**0.882**	**0.920**



NOTE:

For 12 wires, $R^2 = 0.882$ for max force (ES ≤ 0.10 in.) vs. transfer length.

For 9 wires, $R^2 = 0.916$ for max force (ES ≤ 0.10 in.) vs. transfer length.

Figure 4.34 As-received wire regression summary, force at an end slip

4.3.4.2 End Slip at Certain Forces

In this method of analysis, the average end slip at certain forces was compared to the average transfer lengths. The end slip was analyzed for forces ranging from 1000 pounds to 6000 pounds in increments of 500 pounds for all 12 wires. Some of the wire specimens did not reach certain force thresholds due to their lower bond. For example, wire WA is not included in any of these data sets because it never reached the 1000-pound threshold. Any wire not reaching a certain force level was omitted from that particular data set. These omitted wires are indicated in Table 4.9 and Table 4.10 by an absence of data in the end slip, standard deviation, and coefficient of variance (C.V.) columns. The nine-wire data set including only wires with non-continuous indentations was again examined.

The coefficient of determination (R^2) value between end slip and transfer length was calculated for each of the data sets described in the previous paragraph. For brevity, a select few of these results are shown in the main body of this report. Results of the end slip at 1000 pounds force compared with the transfer length can be seen in Table 4.9 and Figure 4.35. The same results at 3500 pounds can be seen in Table 4.10 and Figure 4.36. The entire set of results of pullout force at end slips ranging from 0.01 in. to 0.13 in. in increments of 0.01 in. of end slip can be seen in Appendix G. Figure 4.37 and Figure 4.38 are for the data set including only wires with non-continuous indents.

For clarification, the x-coordinate (abscissa) of each point in these graphs represents the average of six transfer length readings; the y-coordinate (ordinate) of each point in these graphs represents the average of six end slips caused by the indicated applied force. The R^2 is the correlation between these two averaged data sets.

Results of the regression analysis for all applicable wires and for all applicable individually-indented wires are summarized in Table 4.11 and Figure 4.39. The correlation between average end slip and average transfer length (R^2) is plotted at each increment of force. Please note the R^2 value shows no consistent trend for any location of the graph, as was the case for the “force at an end slip” analysis. This indicates this method of analysis is not particularly consistent and could be subject to large biases despite the very high correlation at some locations.

For both data sets, the end slips resulting from 1000 pounds of applied force provide the best correlation to transfer lengths for this method of analysis (end slip at a force). For the data set including all applicable wires, an $R^2 = 0.844$ was achieved. For the nine-wire data set, an $R^2 = 0.943$ was found. However, it should be noted this could be a mere coincidence due to the inconsistency of the correlation data shown in Figure 4.39.

Table 4.9 As-received wires, end slip at 1000 lbf force

As-Received Wire Bond Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
End Slip at 1000 lbf of Force

Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0075	0.00190	25.3	11.6
[WC]	0.0056	0.00114	20.2	8.8
[WD]	0.0067	0.00161	23.9	11.1
[WE]	0.0082	0.00133	16.1	7.4
[WF]	0.0055	0.00066	12.2	8.5
[WG]	0.0095	0.00231	24.3	11.8
[WH]	0.0050	0.00142	28.6	7.5
[WI]	0.0066	0.00106	16.1	10.1
[WJ]	0.0060	0.00148	24.8	9.0
[WK]	0.0117	0.00273	23.4	14.0
[WL]	0.0200	0.00495	24.8	18.7

Note 1: Sample Size = 6
Note 2: A blank entry means the wire didn't reach that force

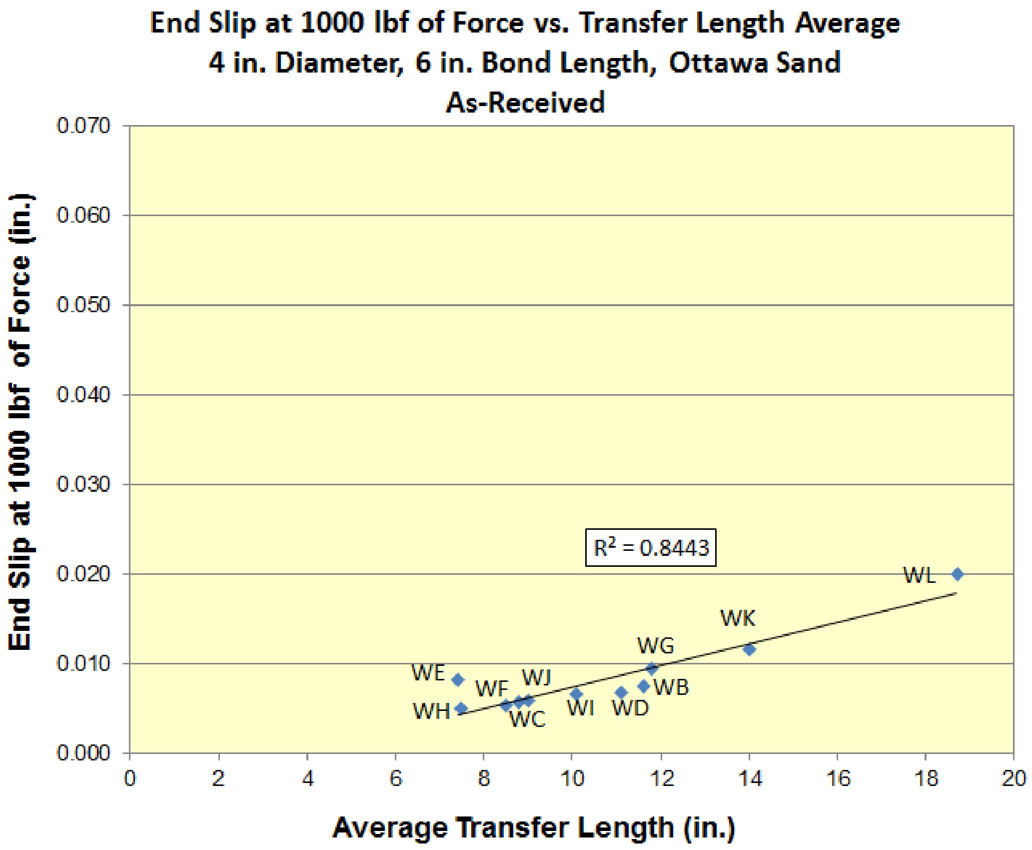


Figure 4.35 As-received wires, end slip at 1000 lbf force

Table 4.10 As-received wires, end slip at 3500 lbf force

As-Received Wire Bond Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
End Slip at 3500 lbf of Force

Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0207	0.00372	17.9	11.6
[WC]	0.0273	0.00459	16.8	8.8
[WD]	0.0189	0.00294	15.5	11.1
[WE]	0.0276	0.00315	11.4	7.4
[WF]	0.0134	0.00135	10.0	8.5
[WG]	0.0322	0.00525	16.3	11.8
[WH]	0.0136	0.00140	10.2	7.5
[WI]	0.0196	0.00238	12.1	10.1
[WJ]	0.0158	0.00296	18.7	9.0
[WK]	0.0611	0.00449	7.3	14.0
[WL]				18.7

Note 1: Sample Size = 6, K = 2
Note 2: A blank entry means the wire didn't reach that force

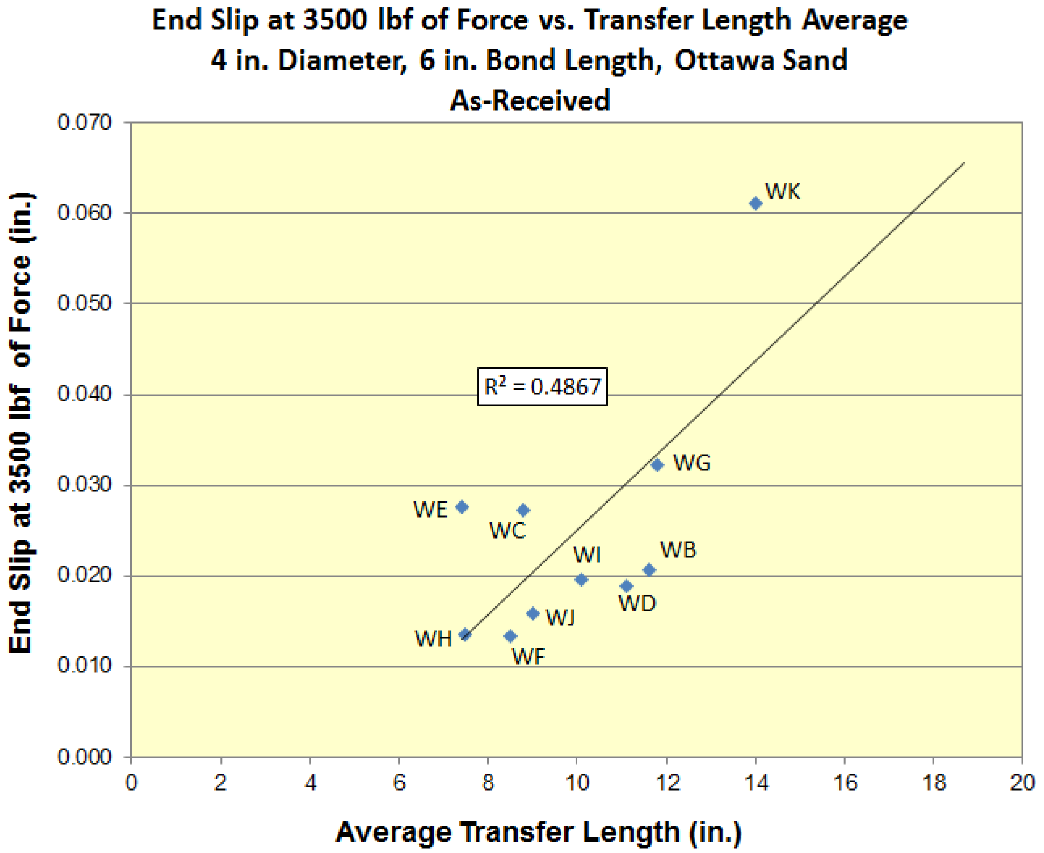


Figure 4.36 As-received wires, end slip at 3500 lbf force

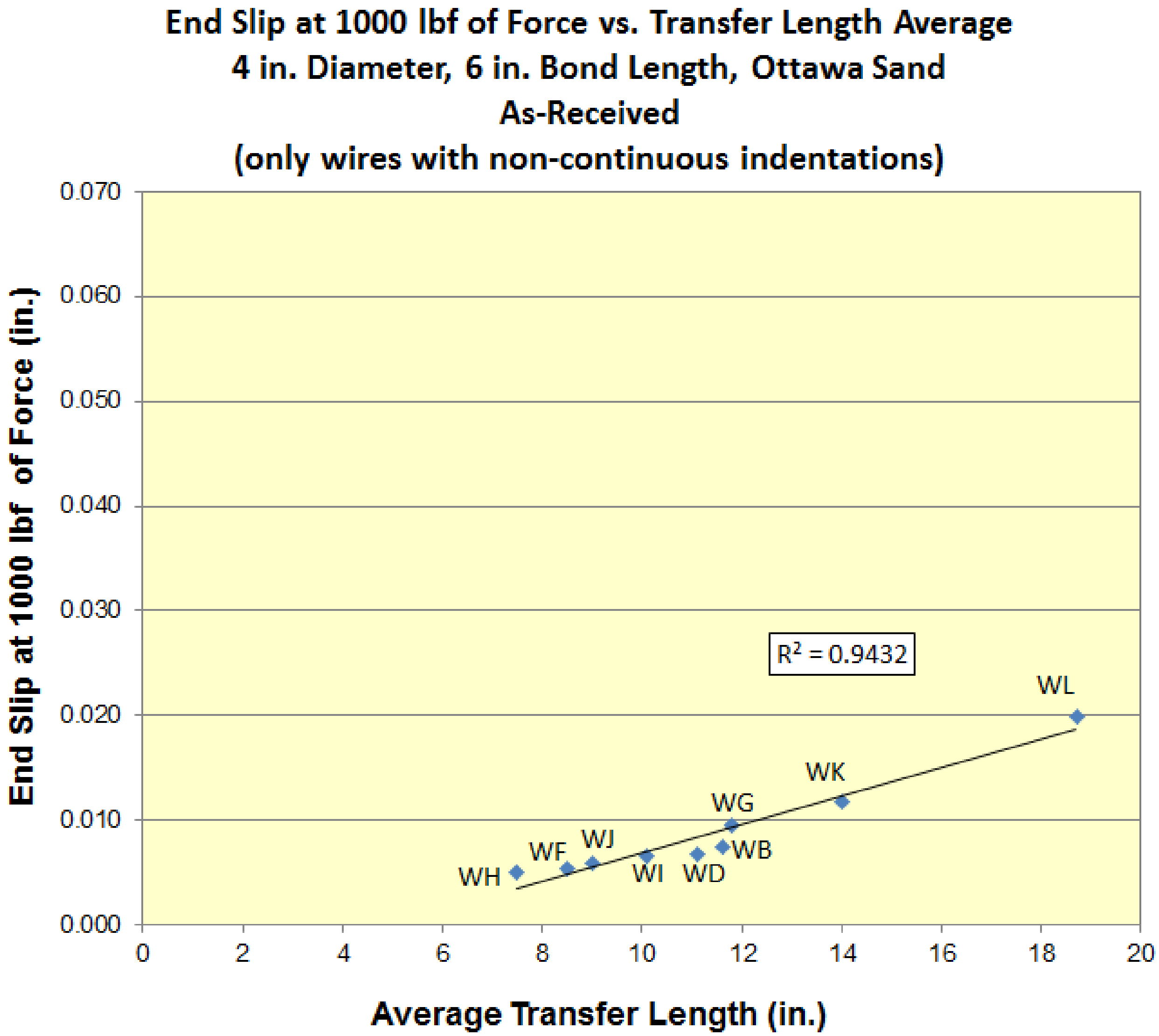


Figure 4.37 As-received wires, end slip at 1000 lbf force (individual-indents only)

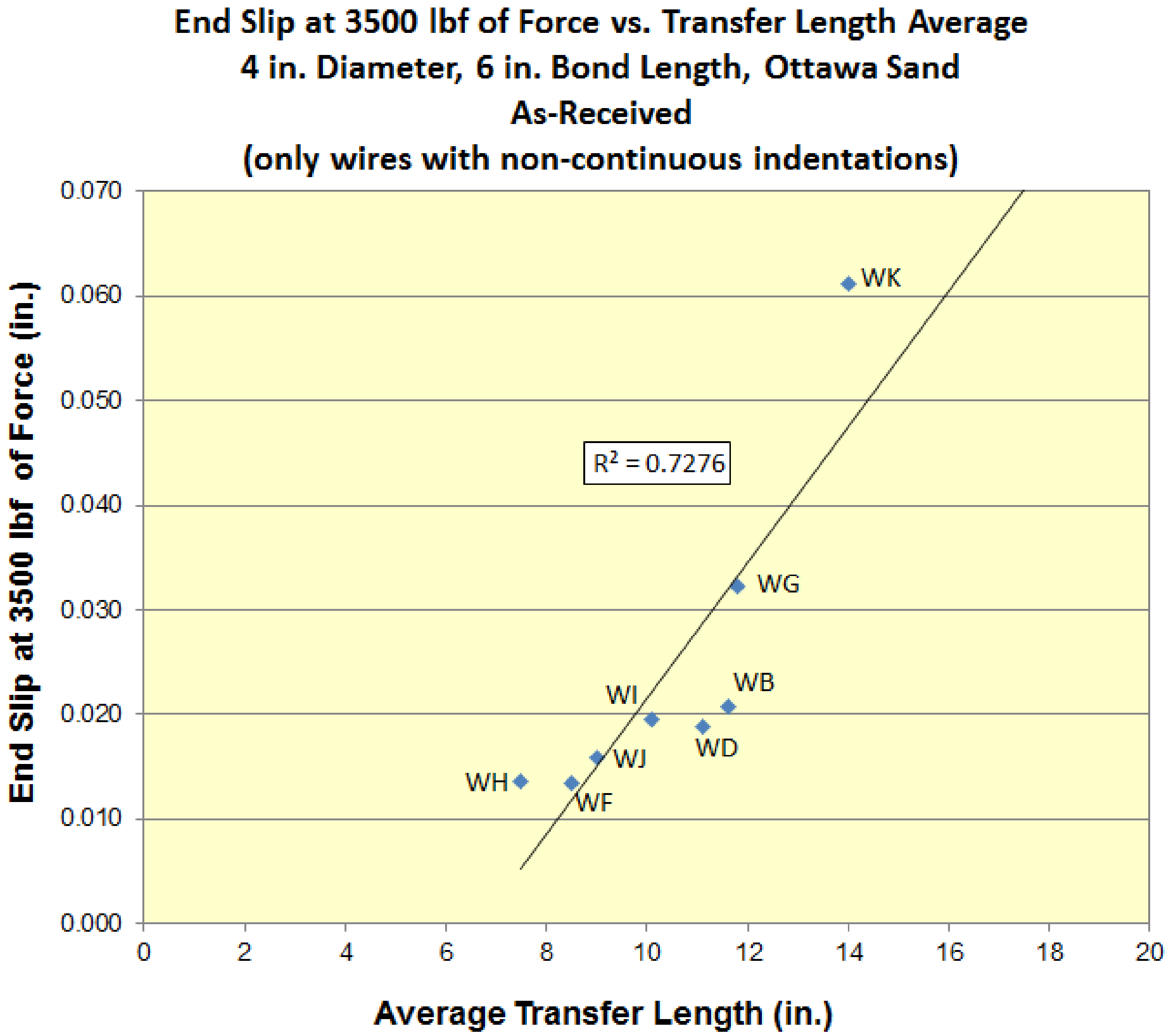


Figure 4.38 As-received wires, end slip at 3500 lbf force (individual-indents only)

Table 4.11 As-received wire regression summary, end slip at a force

Pullout Force (lbf)	R^2	
	All applicable wires	All applicable (individual-indented) wires
1000	0.844	0.943
1500	0.809	0.891
2000	0.792	0.870
2500	0.500	0.743
3000	0.494	0.682
3500	0.487	0.728
4000	0.108	0.657
4500	0.145	0.682
5000	0.212	0.690
5500	0.349	0.912
6000	0.281	0.607
Highest R^2 of set	**0.844**	**0.943**

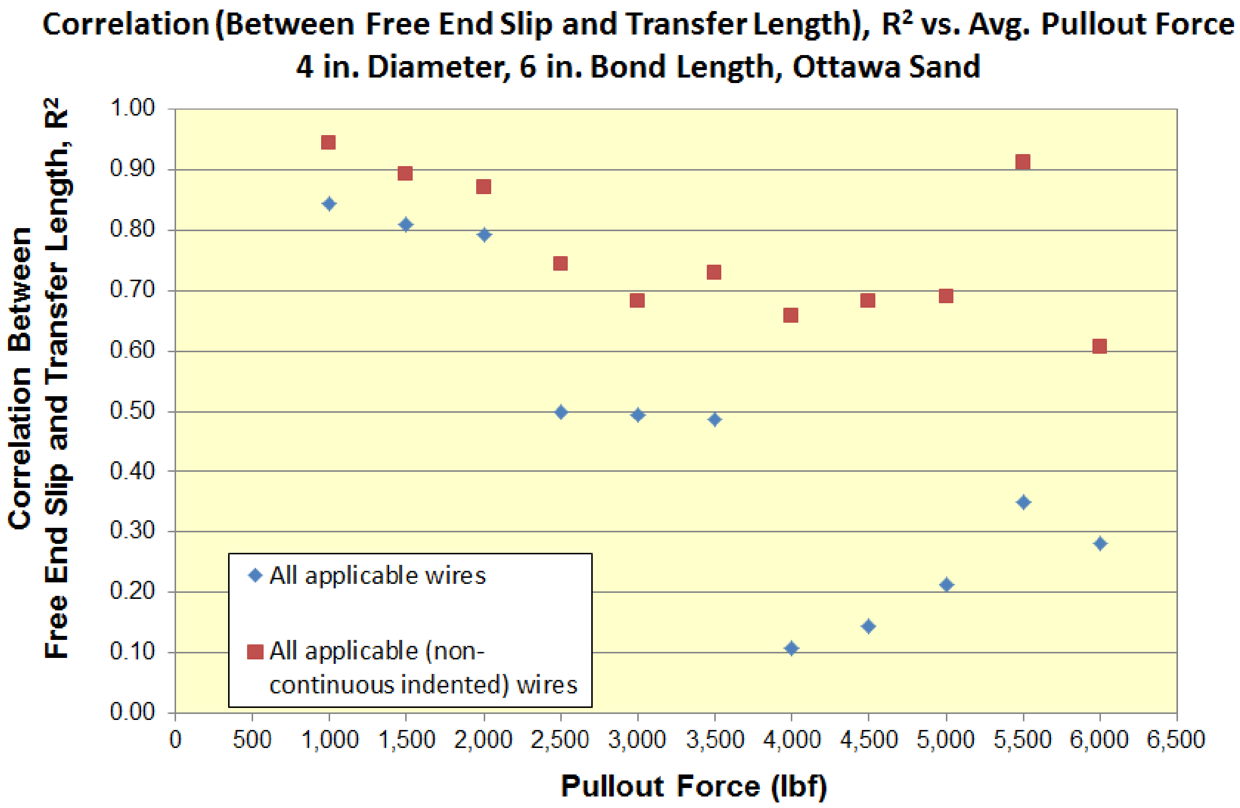


Figure 4.39 As-received wire regression summary, end slip at a force

4.3.4.3 Slope between Two Free-End Slip Values

The third method of analysis compared the average slopes between two end slip values to the average transfer lengths. For this analysis, slope is taken to mean the rise divided by the run of force (rise) vs. end slip (run) graphs. Also, the slopes were approximated to be linear between 0.01 and 0.03 in. of end slip, despite the slight changes in slopes of the actual graphs. This allowed the slope to be calculated as the quantity pullout force at 0.03 in. of end slip minus the pullout force at 0.01 in. of end slip, divided by the quantity 0.03 in. of end slip minus 0.01 in. of end slip. This is represented in tabular form in Table 4.12 and graphically in Figure 4.40.

The forces causing 0.01-in. and 0.03-in. end slip were taken for each individual specimen. The six individual slopes were then averaged to be compared to the average measured transfer lengths of each wire. If the data set did not contain an end slip at both 0.01- and 0.03-in. end slip exactly, then each value was calculated through linear interpolation using the next two closest values. That is, values just below and just above the desired value were used.

The correlation was found for 1) all 12 wires, and 2) for only the wires with non-continuous indentations. This was done because the smooth and spiral wires exhibit a different slip pattern than the chevron indents, and the researchers wanted to see whether or not a good correlation could be achieved for wires with indents specifically conforming to ASTM C881.

For clarification, the x-coordinate (abscissa) of each point in these graphs represents the average of six transfer length readings; the y-coordinate (ordinate) of each point in these graphs represents the average of six graph slopes between 0.01 in. and 0.03 in. of end slip. The R^2 is the correlation between these two averaged data sets.

For the data set including all 12 wires, an $R^2 = 0.673$ for the slope between 0.01 and 0.03 in. of end slip and transfer length was achieved and is shown in Figure 4.41. For the data set excluding the smooth wire and two spiral wires but including the remaining nine wires, an $R^2 = 0.886$ for the slope between 0.01- and 0.03-in. end slip and transfer length was achieved and is shown in Figure 4.42.

Table 4.12 As-received wires, slope between two end slips

Wire Bond Test Results 4 in. Dia, 6 in. Bond Length, Ottawa Sand Slope between 0.01-0.03 in. End Slip		
Wire	Avg. Slope of Individual Graphs (kip/in.)	Transfer Length (in.)
[WA]	-1.7	16.3
[WB]	152.5	11.6
[WC]	107.2	8.8
[WD]	151.3	11.1
[WE]	126.5	7.4
[WF]	217.9	8.5
[WG]	113.3	11.8
[WH]	186.7	7.5
[WI]	163.1	10.1
[WJ]	179.2	9.0
[WK]	69.7	14.0
[WL]	39.1	18.7

Note 1: Sample size = 6

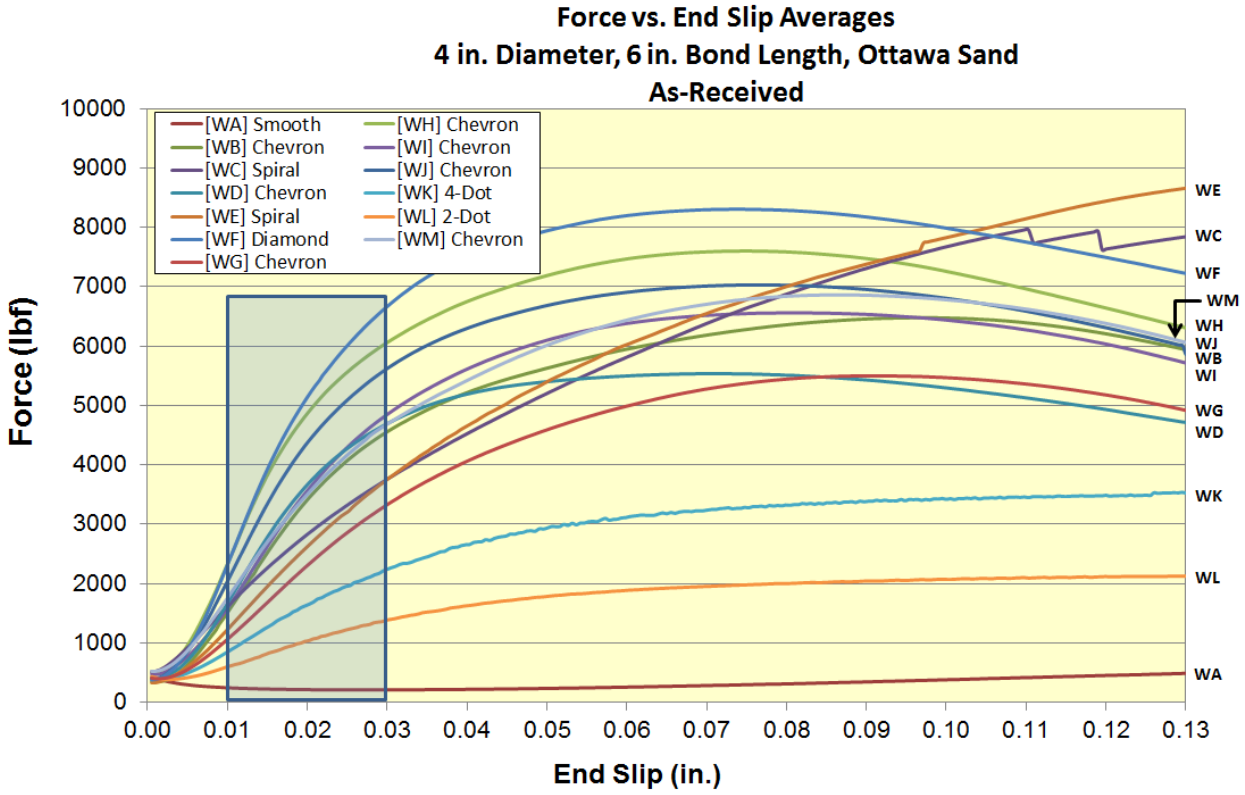


Figure 4.40 As-received wires, slope between two end slips

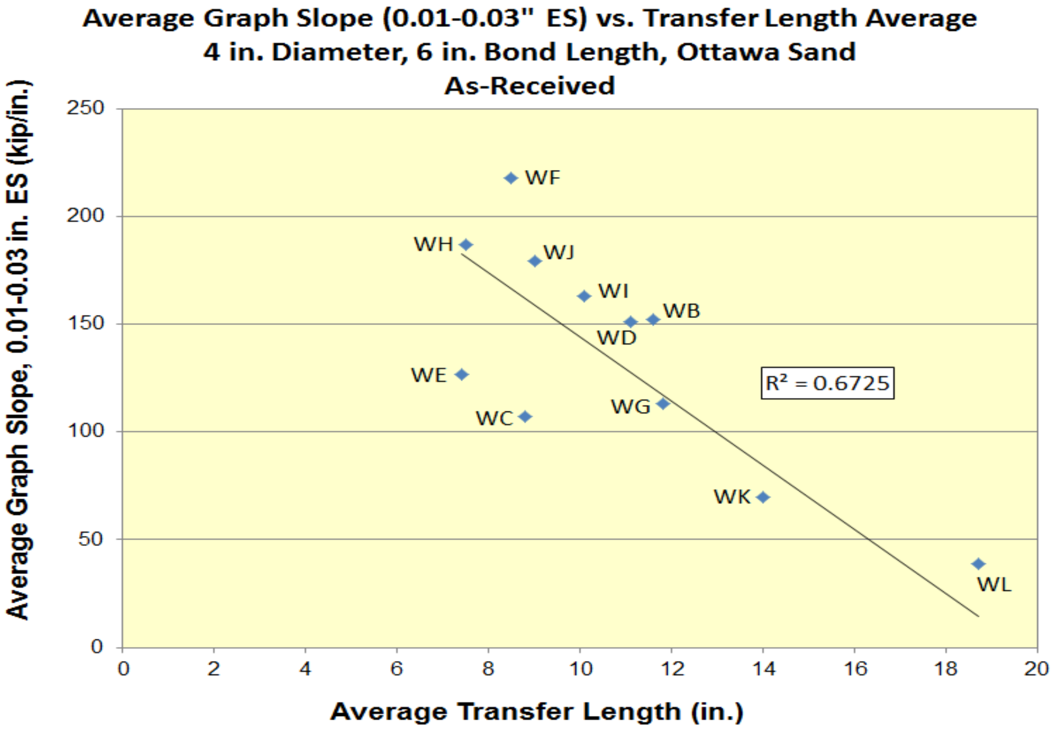


Figure 4.41 As-received wires, slope between 0.01 and 0.03 in. end slip

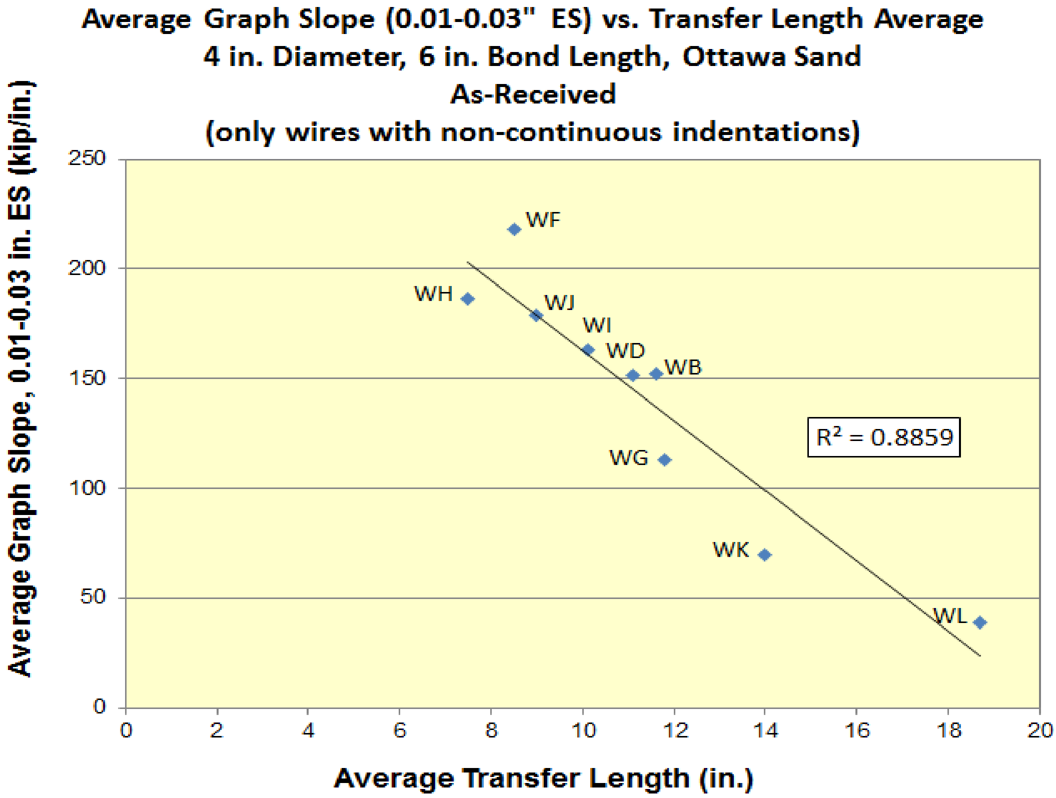


Figure 4.42 As-received wires, slope between 0.01 and 0.03 in. end slip (individual-indents only)

4.3.4.4 Slope between Two Force Values

The fourth method of analysis compared the average slopes between two forces to the average transfer lengths. For this analysis, slope is taken to mean the rise divided by the run of force (rise) vs. end slip (run) graphs. Also, the slopes were approximated to be linear between 1000 and 4000 pounds of force despite the slight changes in slopes of the actual graphs. This allowed the slope to be calculated as the quantity 4000 pounds of pullout force minus the 1000 pounds of pullout force, divided by the quantity end slip at 4000 pounds force minus end slip at 1000 pounds force. This is represented in tabular form in Table 4.13 and graphically in Figure 4.43.

The end slips resulting from 1000 and 4000 pounds force were taken for each individual specimen. The six individual slopes were then averaged to be compared to the average measured transfer lengths of each wire. If the data set did not contain a force at both 1000 and 4000 pounds force exactly, then each value was calculated through linear interpolation using the next two closest values. That is, values just below and just above the desired value were used.

Some of the wire specimens did not reach 4000 pounds of force due to their lower bond. Any wire not reaching at least 4000 pounds was omitted from this analysis method. These omitted wires are indicated in Table 4.13 by an absence of data in the average slope column.

The correlation was found for 1) all applicable wires, and 2) for only the wires with non-continuous indentations. This was done because the smooth and spiral wires exhibit a different slip pattern than the chevron indents, and the researchers wanted to see whether or not a good correlation could be achieved for wires with indents specifically conforming to ASTM C881.

For clarification, the x-coordinate (abscissa) of each point in these graphs represents the average of six transfer length readings; the y-coordinate (ordinate) of each point in these graphs represents the average of six graph slopes between 1000 and 4000 pounds of applied force. The R^2 is the correlation between these two averaged data sets.

For the data set including all applicable wires, an $R^2 = 0.130$ for the slope between 1000 and 4000 pounds force and transfer length was achieved and is shown in Figure 4.44. For the data set excluding the smooth wire and two spiral wires but including the remaining applicable wires, an $R^2 = 0.809$ for the slope between 1000 and 4000 pounds force and transfer length was achieved and is shown in Figure 4.45.

Table 4.13 As-received wires, slope between two forces

Wire Bond Test Results
4 in. Dia, 6 in. Bond Length, Ottawa Sand
Slope between 1000-4000 lbf

Wire	Avg. Slope of Individual Graphs (kip/in.)	Transfer Length (in.)
[WA]		16.3
[WB]	179.2	11.6
[WC]	111.1	8.8
[WD]	196.5	11.1
[WE]	125.2	7.4
[WF]	314.1	8.5
[WG]	103.0	11.8
[WH]	285.6	7.5
[WI]	188.4	10.1
[WJ]	252.8	9.0
[WK]		14.0
[WL]		18.7

Note 1: Sample size = 6

Note 2: A blank entry means the wire never reached 4000 pounds

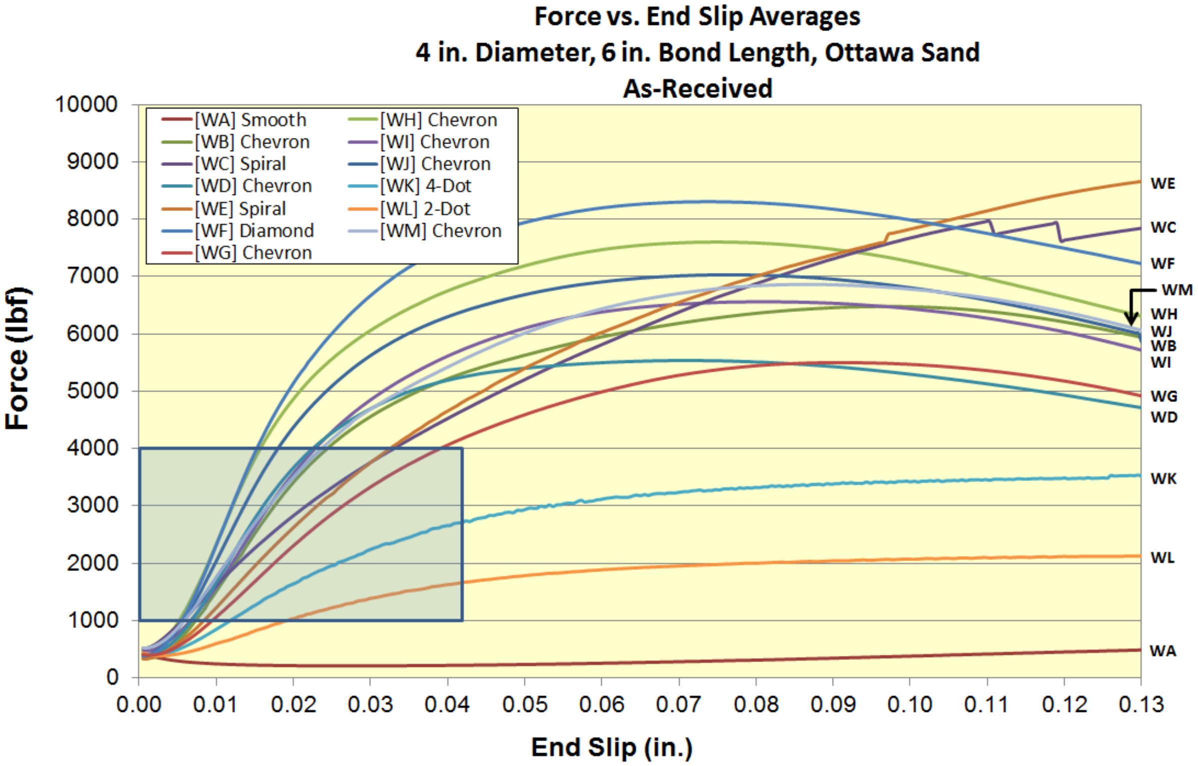


Figure 4.43 As-received wires, slope between two forces

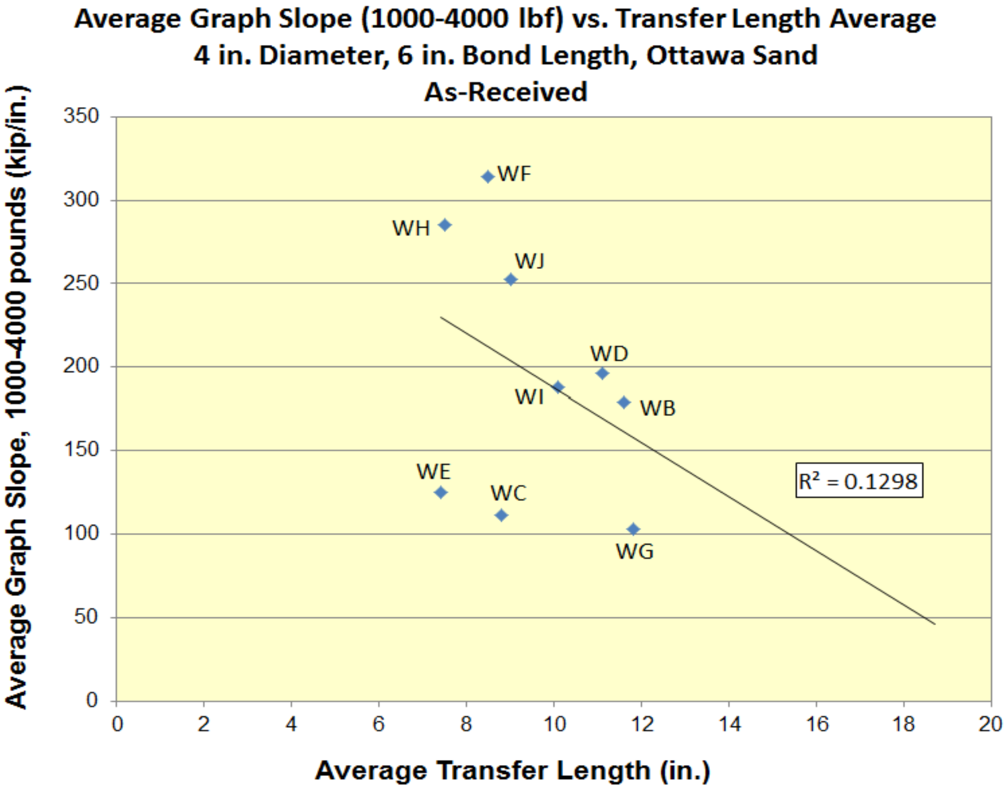


Figure 4.44 As-received wires, slope between 1000 and 4000 pounds force

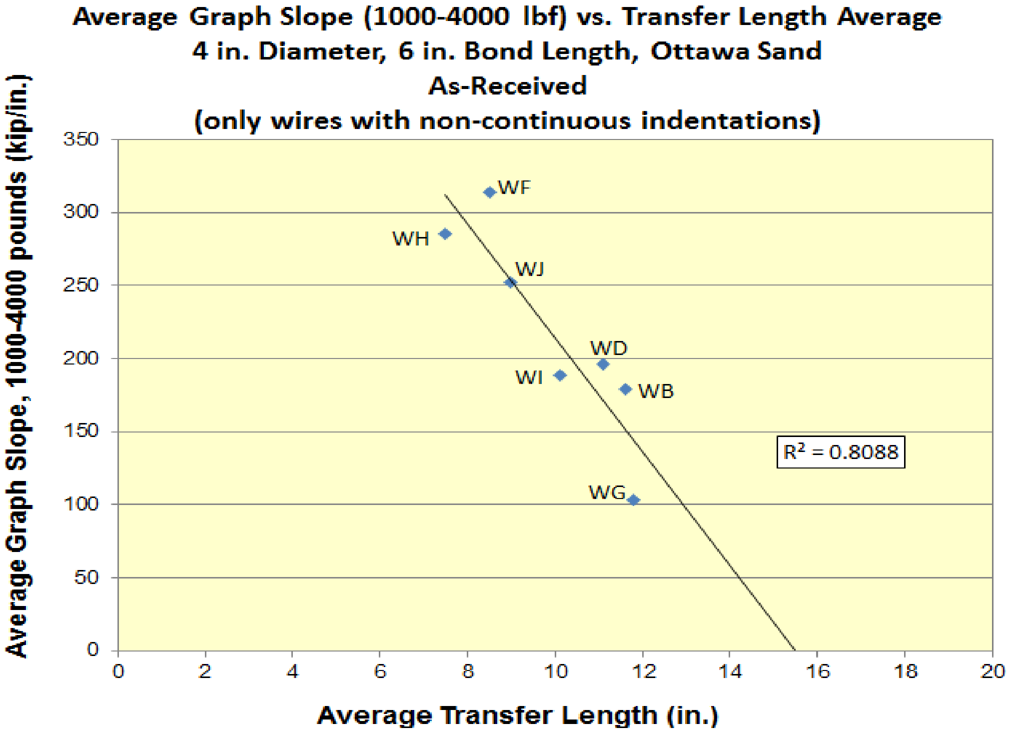


Figure 4.45 As-received wires, slope between 1000 and 4000 pounds force (individual-indents only)

4.3.4.5 Best Analysis Method for Wires

Results of the four different methods of analysis are shown in Table 4.14. When considering these four methods of analysis, one might initially assume the best correlation comes from using the end slip at 1000 pounds of applied force (R^2 = 0.943). However, when considering the data presented in Figure 4.39, the inconsistent trend of the data indicates this method of analysis could be subject to large biases despite the very high correlation at some locations.

When maximum correlation and consistency of the data are used jointly to select the best method of analysis, it can be seen the maximum pullout force at any location less than or equal to 0.10-in. end slip should be selected. This analysis gives a correlation of R^2 = 0.916 when considering only the wires with non-continuous indentations. Furthermore, this method of analysis also provides the highest correlation of R^2 = 0.884 when all 12 wires are considered. These results show that when using the wire pullout test described in Appendix I, this method of analysis should be the most accurate predictor of the wire's transfer length.

From this point forward, the result of the wire bond test should be taken as the maximum load recorded at a free-end slip less than or equal to 0.10 in.

Table 4.14 Summary of four methods of wire regression analysis, best correlations

Method of Analysis	Best R^2 achieved for all wires	Best R^2 achieved for individual-indents only	Location where best R^2 occurs	Notes
1) Force at Certain End Slips	0.882	0.916	Max force (ES ≤ 0.10 in.)	9 wires (individual-indent only)
2) End Slip at Certain Forces	0.844	0.943	1000 pounds force	All applicable individual-indent Inconsistent data trend
3) Slope between Two End Slips	0.673	0.886	0.01 in. to 0.03 in. ES	9 wires (individual-indent only)
4) Slope between Two Forces	0.130	0.809	1000 to 4000 pounds force	All applicable individual-indent

4.3.5 Verification of As-Received Results

The 13th wire, WM, was used to verify the results of the as-received wire pullout test model. This wire was not used in any development of the wire bond pullout test. Moreover, this wire did not even arrive at the testing facility until after completion of the development program.

The as-received regression analysis using only wires with non-continuous indentations was used to predict the transfer length of WM. The model generated by this data set is shown in Figure 4.46 and is the same data used to obtain Figure 4.33 from Section 4.3.4.1 (with the axes switched). Equation 4.1, obtained from the model in Figure 4.46, gives the equation of the expected transfer length of as-received, indented prestressing wires. Please note this equation gives the expected transfer length for 4-in. square prisms in a similar concrete with a 4500 psi release strength.

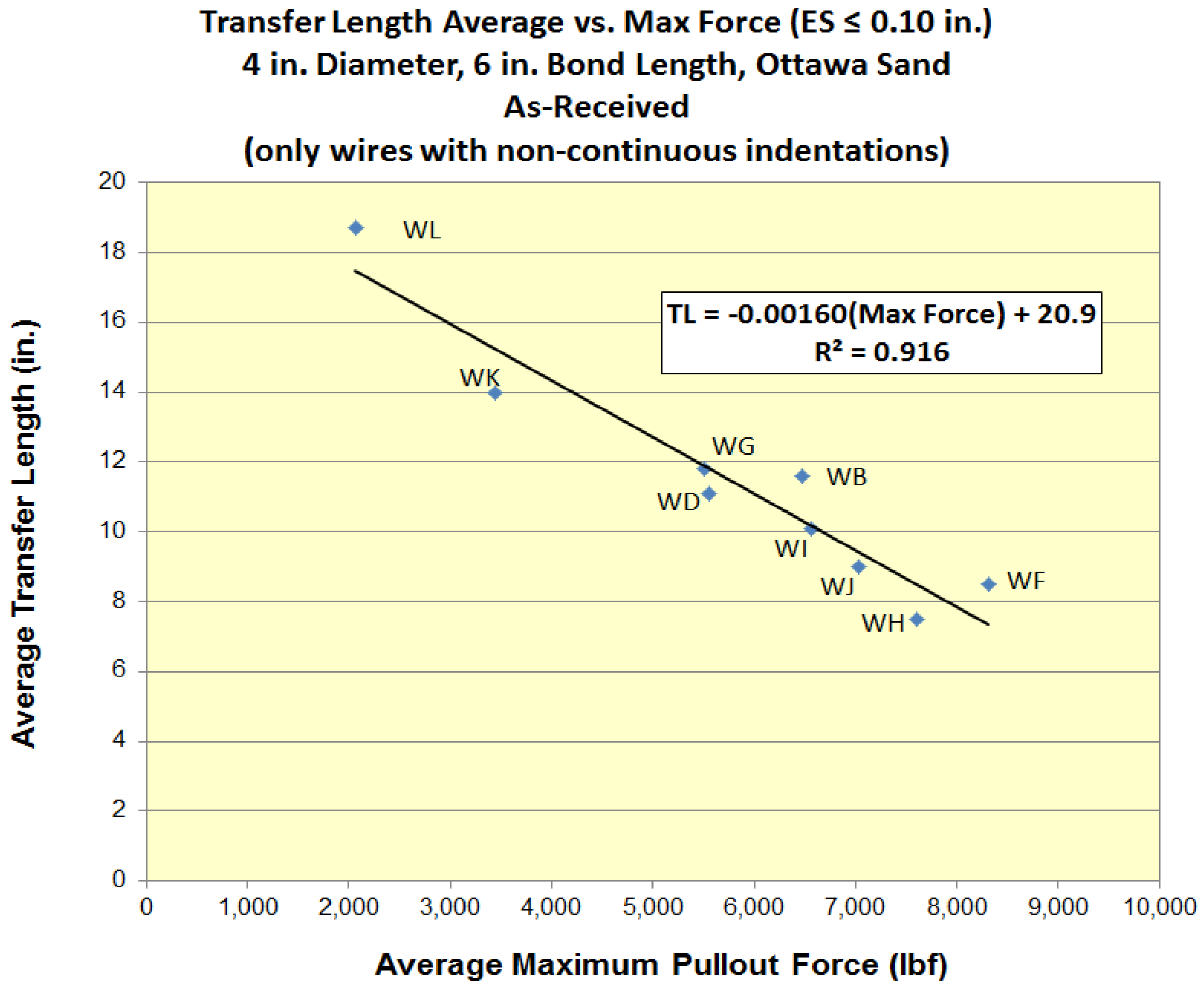


Figure 4.46 As-received wires, transfer length prediction model

$$\boldsymbol{TL = -0.00160(Max\ Force) + 20.9} \qquad \text{Equation 4.1}$$

where TL = expected as-received transfer length from prisms

$Max\ Force$ = maximum force ≤ 0.10 in. end slip

After the model was built, six pullout tests were performed on wire WM in their as-received condition to test whether its transfer length could be predicted. The data was obtained the same way as all of the other wires. Results were compiled and maximum pullout force values (occurring at an end slip less than or equal to 0.l0 in.) for each as-received WM specimen are shown in Table 4.15. The pullout force vs. end slip graphs for the six individual as-received WM specimens are shown in Figure 4.47.

Using the average maximum force of 6879 pounds obtained from Table 4.15 and Equation 4.1, the predicted transfer length of wire WM using the as-received model is 9.9 inches. The average measured transfer length – using six transfer length measurements – from the pretensioned prisms was found to be 9.8 inches in the lab. The difference of the expected (theoretical) transfer length from the actual (experimental) transfer length is 0.1-in., an error of 1.0%. For the given force (6879 lbf) and using a confidence interval of 95%, the predictive equation (Equation 4.1) gives an predicted range of approximately 8.7-in. to 10.8-in. The results of WM fall within this range.

Figure 4.48 shows the average maximum force of the six pullout tests using WM in its as-received condition compared to the average of the six measured transfer length measurements. The predictive model (from Figure 4.46) is also shown in Figure 4.48 for visual comparison along with the predicted range given by a 95% confidence interval.

This analysis shows the wire pullout test described in Appendix I is an excellent predictor of transfer length for as-received wires with non-continuous indentations. The predicted (theoretical) transfer length of 9.9 in. and an actual (experimental) transfer length of 9.8 in. were almost identical for wire WM in its as-received condition.

Table 4.15 As-received maximum force values for six [WM] specimens

As- Received [WM]	
Specimen #	Max Force (lbf)
1	6734
2	7642
3	6063
4	6651
5	6857
6	7325
Average	6879

Std. Dev. (lbf) = 503

Coeff. of Variation, C.V. (%) = 7.3

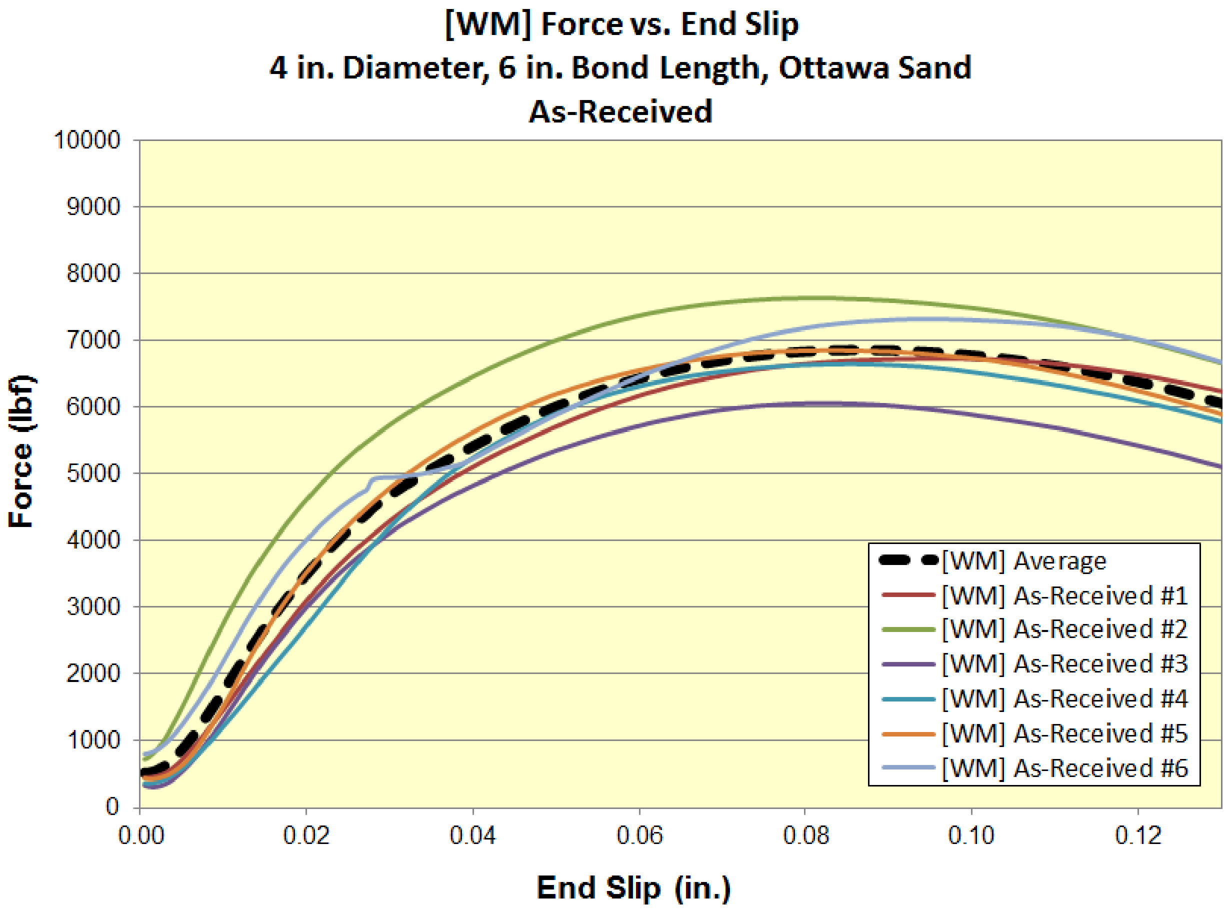


Figure 4.47 As-received [WM] force vs. end slip graphs (individual and average)

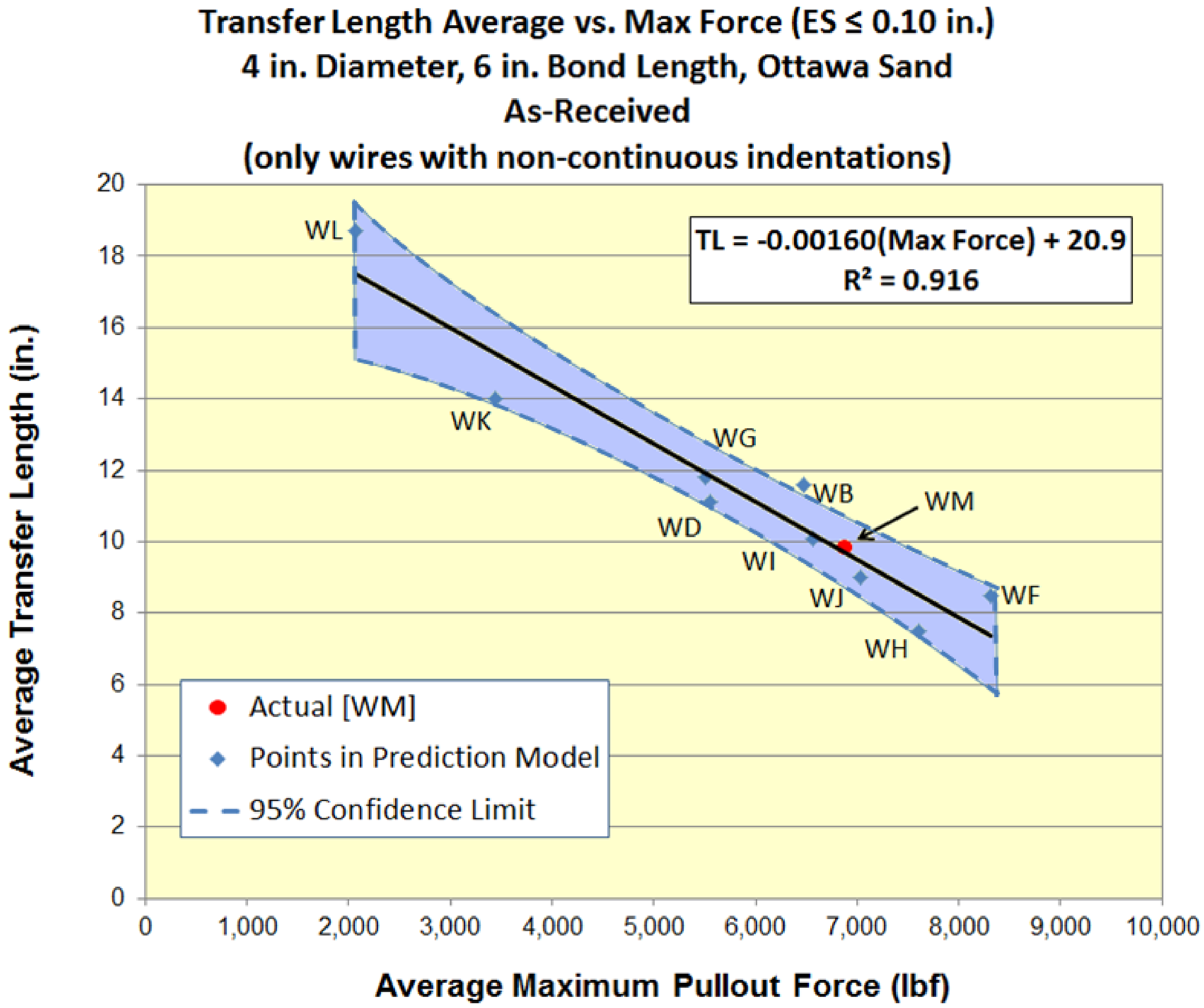


Figure 4.48 As-received wires, [WM] compared with predictive model

4.3.6 Comparison of As-Received vs. Cleaned

The analysis in this section compared results from Section 4.3.1 (as-received wire pullout data) to results from Section 4.3.2 (cleaned wire pullout data). This section directly compares results of the as-received and cleaned wire specimens. This issue focuses on differentiating between bond associated with indent geometry and bond associated with surface condition.

Seven wires (WA, WE, WF, WG, WH, WK, and WM) were tested both in their as-received and cleaned conditions. Of these wires, WG and WM exhibited slight to moderate levels of rusting. Wire WK appeared to have a very slight residue coating the surface. The remaining four wires (WA, WE, WF, WH) appeared to have no noticeable signs of either rust or oils. Due to these different surface conditions, it was hypothesized that wires WG and WM may perform slightly worse after being cleaned due to having the rust removed. Slight rusting has been shown to improve bond performance during similar testing done on strands (Gustavson, 2004; Rose and Russell, 1997; Barnes, Grove, and Burns, 2003). Similarly, it was originally thought wire WK would exhibit better bond after being cleaned due to having the oil removed. It was assumed the remaining four wires would show roughly the same bond performance before and after the cleaning process.

The average pullout force vs. end slip graph for each wire is shown in Figure 4.49 through Figure 4.55. Each "as-received" and "cleaned" line on the graphs represents the six averaged specimens for those respective tests. Results of the individual pullout tests comparing six as-received specimens to six cleaned specimens can be seen in Appendix H.

From Figure 4.49 through Figure 4.55, it can be seen that none of the seven wires performed much differently before or after the cleaning process, especially in the ascending branch. Wires WG and WM actually performed slightly better after cleaning, which was the opposite of the assumed performance. Wire WK also performed slightly better after being cleaned during its initial phases of slip, but after reaching approximately 0.06 in. of end slip, the bond performances were almost identical.

None of the wires exhibited a vast discrepancy in bond performance when comparing the as-received specimens to the cleaned specimens. Due to this similarity in bond performance, one of two conclusions can be made:

1) All seven of the wires tested for cleaning had roughly the same combination of surface lubricants and/or rusting that affected them all equally.
2) The bond performance of a wire is dominated by the indent geometry and only minimally affected by the surface condition as long as the surface is relatively clean.

Because of the visibly different surface conditions documented by the researchers, coupled with the knowledge that the seven wires selected for cleaning were manufactured by six different companies, the first conclusion is very implausible. The latter conclusion makes sense when the overall geometry of the wire is considered. Since the area of the wire indents is large relative to the overall cross-sectional area of the 5.32-mm-diameter wire, it makes sense that the indent geometry would govern the overall bond performance of the wires.

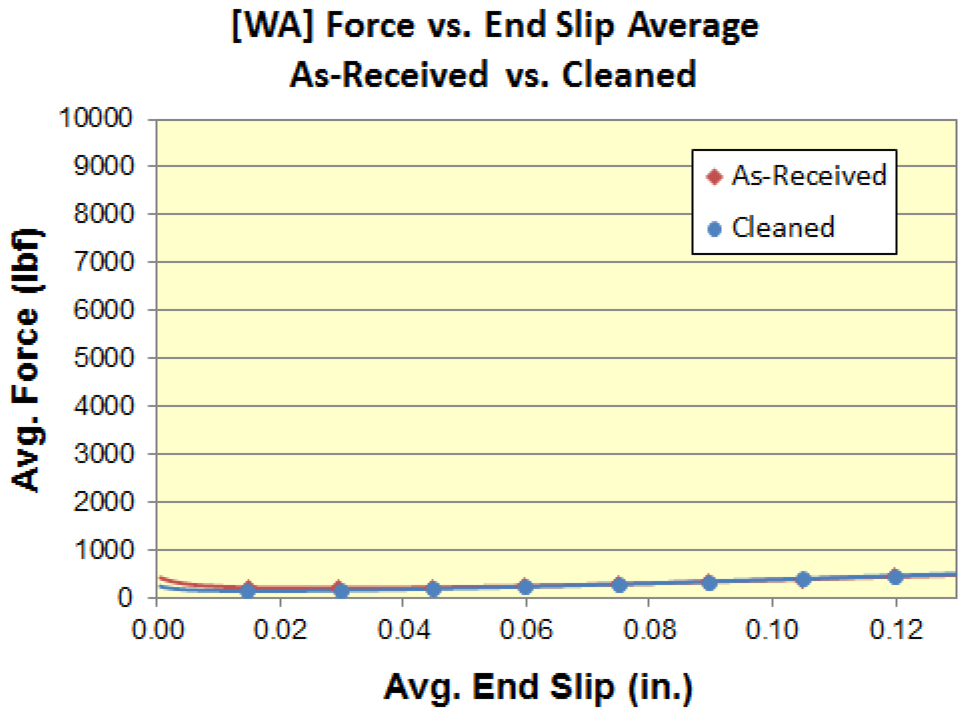


Figure 4.49 [WA] force vs. end slip average graphs, as-received vs. cleaned

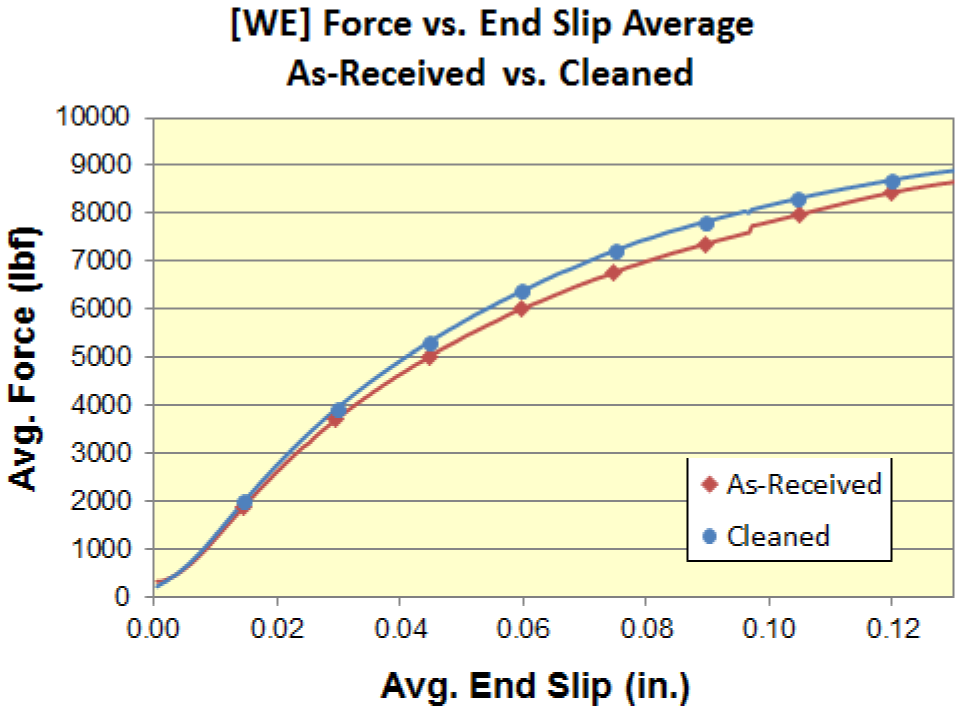


Figure 4.50 [WE] force vs. end slip average graphs, as-received vs. cleaned

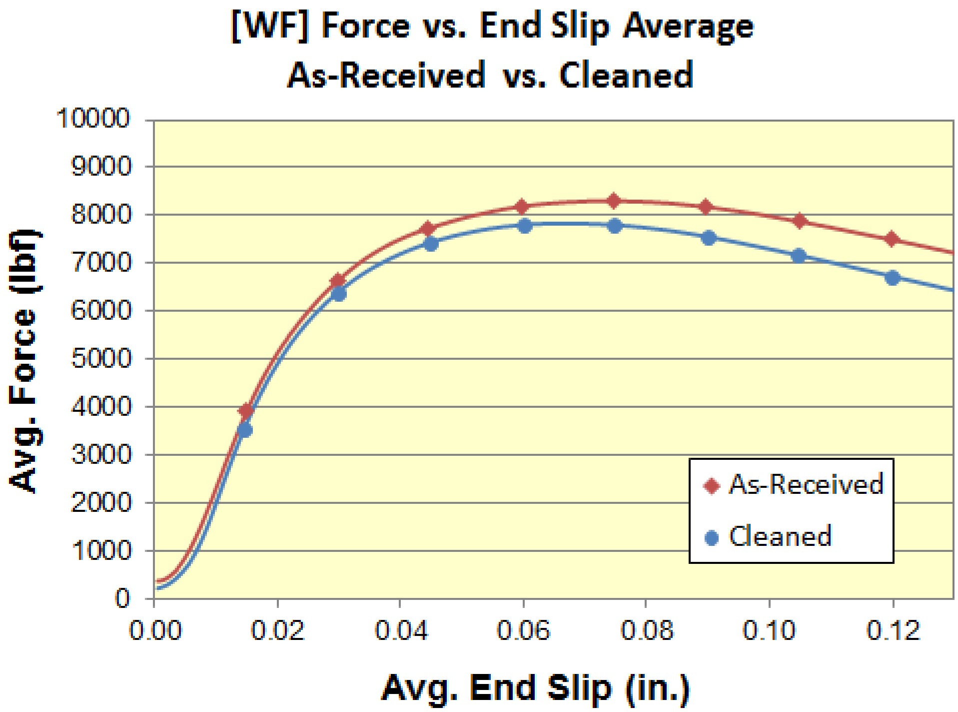


Figure 4.51 [WF] force vs. end slip average graphs, as-received vs. cleaned

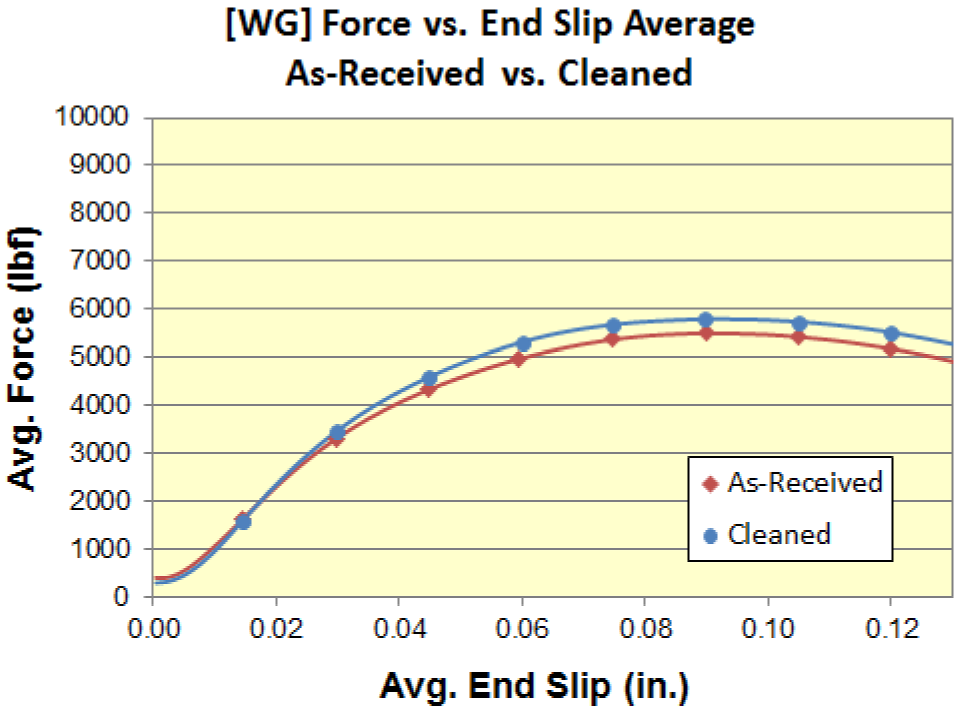


Figure 4.52 [WG] force vs. end slip average graphs, as-received vs. cleaned

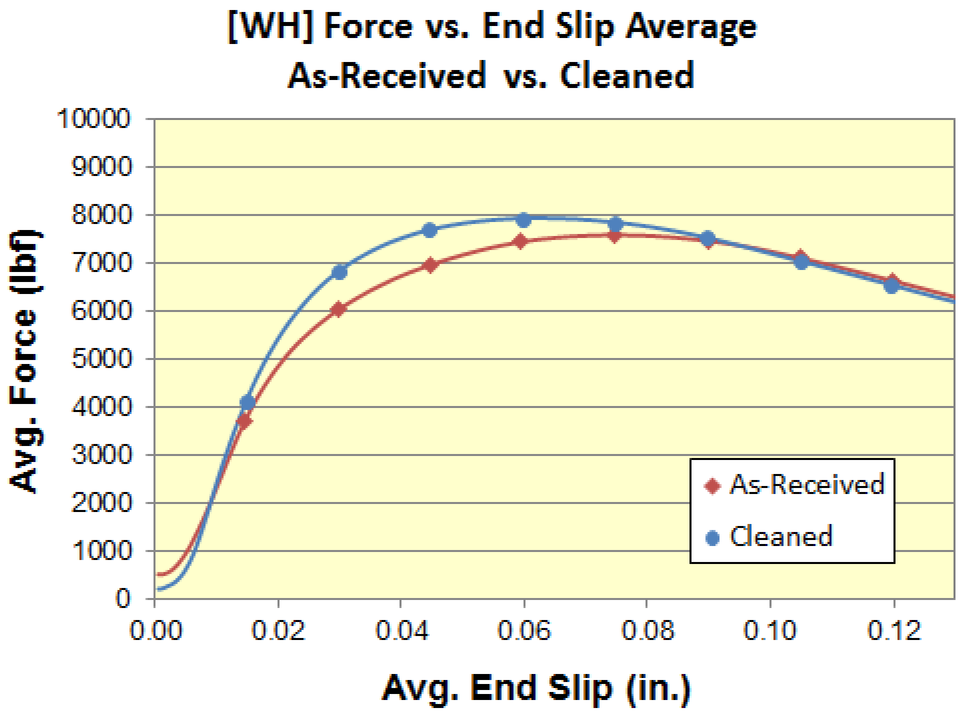


Figure 4.53 [WH] force vs. end slip average graphs, as-received vs. cleaned

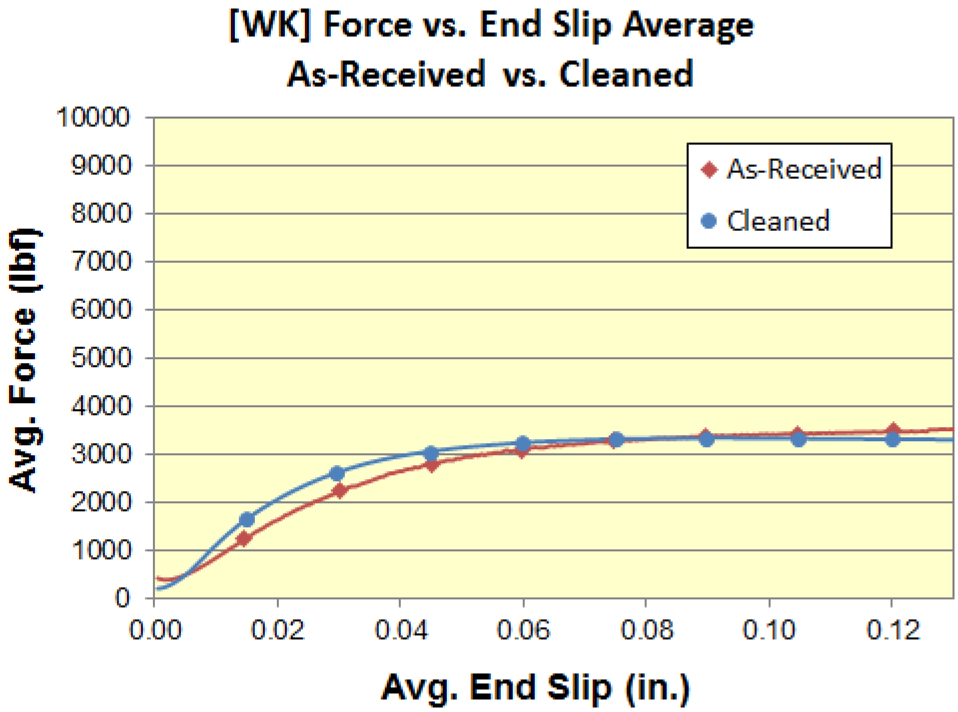


Figure 4.54 [WK] force vs. end slip average graphs, as-received vs. cleaned

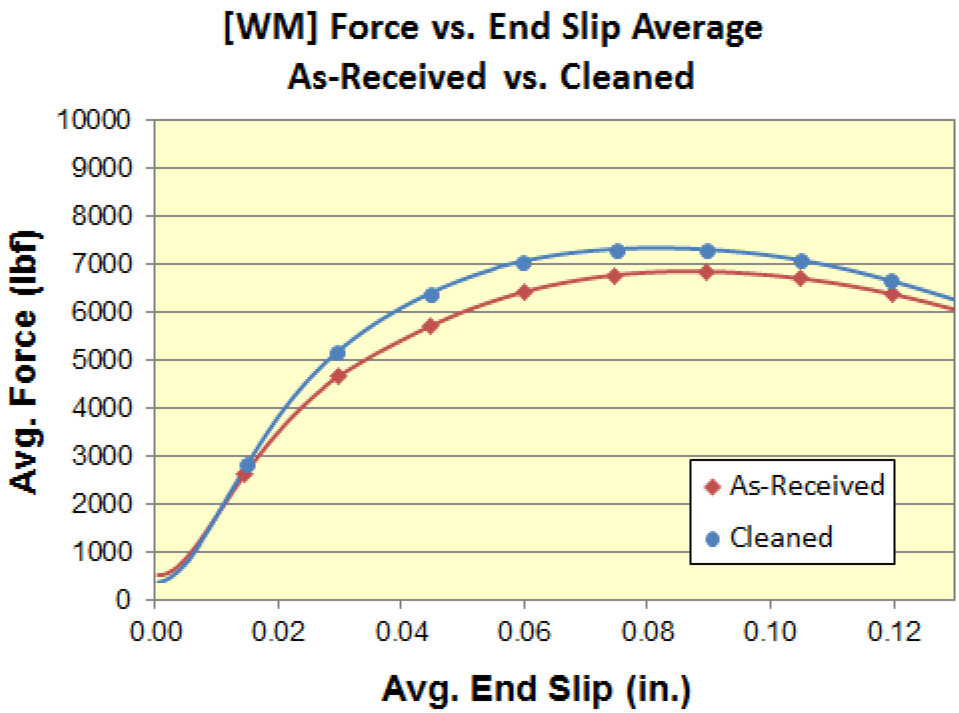


Figure 4.55 [WM] force vs. end slip average graphs, as-received vs. cleaned

Chapter 5 - Lab Phase; Strand Pullout Testing (Un-tensioned Tests in Mortar)

Chapter 5 discusses the experimental program, results, and analysis of the lab portion of the strand bond pullout tests. These tests are un-tensioned and were performed in mortar.

5.1 Using the Strand Bond Test as a Basis

The Standard Test for Strand Bond was used as a basis for strand bond testing performed in this experimental testing program. The general testing procedure set forth in Ramirez and Russell (2008) was used for the tests presented here. Please note, at the time, no requirement on use of a neoprene rubber pad was in the specifications and was not used at Kansas State University.

The primary goal of this lab phase was to provide evidence in favor of expanding the strand bond test to include smaller diameter strands (less than 0.5 in.). This testing program sought first to verify whether or not a 16-in. bond length used for the Standard Test for Strand Bond would be adequate for smaller diameter strands. If the 16-in. bond length was determined to be inadequate (too long), then a modified version of the standard strand bond test would be proposed for smaller diameter strands. Preferably, all parameters except bond length would remain the same as the standard strand bond test.

5.2 Experimental Program

This section contains information used for this experimental testing program regarding the verification of the Standard Test for Strand Bond (Ramirez and Russell, 2008) for seven-wire and three-wire strands with diameters smaller than 0.5 in. This information includes research variables; specimen dimensions; mix proportions, material sources, and match sizes; specimen casting and storage procedures; and testing procedures used to verify the un-tensioned pullout test for smaller diameter strands.

5.2.1 Research Variables

Three primary research variables for the strand testing portion of the lab phase are strand and indent geometry, surface condition, and bond length. The first two are of great importance because they allow the researchers to better distinguish what portion of a reinforcement's bond performance can be attributed to the surface and indent geometry, and what portion can be attributed to the surface condition. These two effects were investigated by testing the reinforcements in both their "as-received" and "cleaned" conditions.

In total, six different strands with different indentation patterns from four different steel manufacturers were used to develop the un-tensioned pullout test described in detail in Chapter 5. All strands were Grade 270, low-relaxation strands. Some strands were 5/16-in.-diameter and some were 3/8-in.-diameter. Additionally, some were three-wire strands and some were seven-wire strands. The strands were stored in 25 foot lengths in PVC tubes with silica-based desiccant packets to prevent any rusting and preserve the wires' "as-received" surface condition for testing.

First, the strand and indentation geometry of the steel prestressing strands was investigated by testing the wires with their "as-received" surface conditions. This allowed for the relative bond performance of the wires to be examined and to establish a baseline for expected bond performance.

Second, the surface condition of the strands was tested by cleaning the strands. This occurred by performing further pullout testing on all six of the strands after being subjected to the cleaning process described in depth in Section 3.3. The "cleaned" specimen tests were performed on bare steel by removing rust, oils, and surface lubricants with an acidic solution.

Results of these "cleaned" specimens were compared to the "as-received" specimens. This process allowed the researchers to better separate out the bond attributed to surface condition from the bond attributed to surface and indent geometry.

The testing matrix for the strand pullout tests can be seen in Table 5.1. Each strand was tested six times and the results averaged to give the expected bond performance of each wire. Both the "as-received" and "cleaned" strand pullout results were compared to the measured transfer length of accompanying pre-tensioned prisms. These prisms were cast using a concrete mixture similar to one used in a major concrete tie manufacturing plant in the United States. The batching and testing procedures used to obtain the transfer lengths from these pre-tensioned prisms are presented in Bodapati's 2013 paper, but are not discussed here.

Additionally, a third parameter was looked at for strand testing: bond length. This is significant for the smaller diameter strands (less than 0.5 in.), as they are not able to handle as much load before rupturing due to decreased surface and cross-sectional areas compared with larger diameter strands (0.5 in and larger). This testing program sought first to verify if a 16-in. bond length used for the Standard Test for Strand Bond (Ramirez and Russell, 2008) would be adequate for smaller diameter strands. If the 16-in. bond length was determined to be inadequate (too long), then a modified version of the standard strand bond test would be proposed for smaller diameter strands. Preferably, all parameters except bond length would remain the same as the standard strand bond test.

Table 5.1 Matrix of strand pullout testing program (lab phase)

Strand Manufacturer	Strand Identification	Indentation Type	Number of test specimens		
			Transfer lengths (no. of ends)	As-received un-tensioned pullouts	Cleaned un-tensioned pullouts
A	[SA]	3/8" 7-Wire, Smooth	6	12	6
A	[SB]	3/8" 7-Wire, Indented	6	12	6
A	[SC]	5/16" 3-Wire, Smooth	6	12	6
B	[SD]	3/8" 7-Wire, Indented	6	12	6
C	[SE]	3/8" 7-Wire, Indented	6	12	6
D	[SF]	3/8" 3-Wire, Indented	6	12	6
Total:			**36**	**72**	**36**

Note: (6) of the "as-received" strand specimens were tested both at a 16 in. bond length and a 9 in. bond length.

5.2.2 Specimen Dimensions

Two specimen sizes were used for the strand bonding portion of the lab phase. The first specimen was the exact same size used for the strand bond test and will be referred to as either the “standard length strand specimen” or the “16-in. specimen” for the remainder of this paper. The second specimen was a modified version of the ones used to develop the Strand Bond Test. These modified specimens will be referred to as either the “short-length specimen” or the “9-in. specimen” for the rest of this paper.

The standard length specimens utilized a 5-in.-outer-diameter steel tube, 1/8-in. wall thickness, and a total length of 18 in. A 6-in. by 6-in. steel plate (3/16-in. thick) was tack welded to the bottom. The remaining contact surface between the tube and bottom plate was caulked to prevent any leakage. Within the 18-in. long steel tube, there was a 16-in. embedment (bond) length with a 2-in. long foam-tape bond breaker at the bottom. The strand extended past the top mortar surface approximately two inches. A schematic of the 16-in. pullout specimen is shown in Figure 5.1. The 5-in.-diameter steel tubes were able to be re-used by cutting the tack welds, removing the bottom plate, and pushing out the mortar (with a hydraulic actuator and specially-made frame).

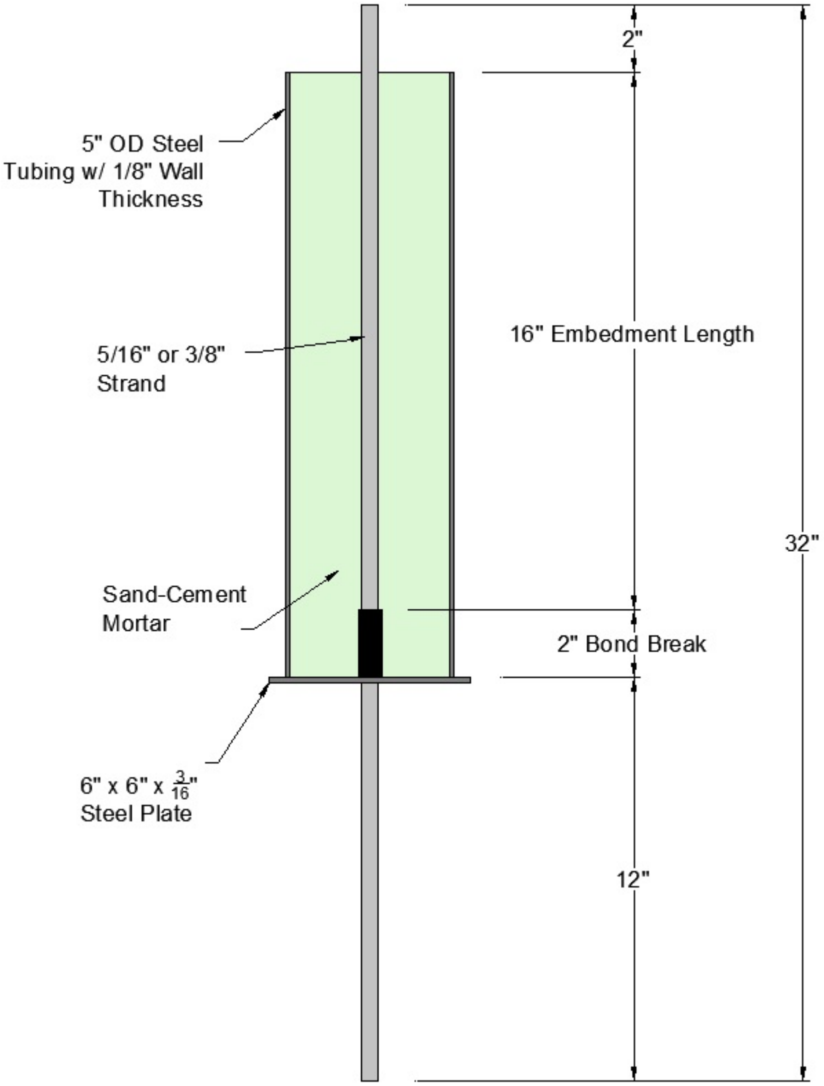


Figure 5.1 Dimensions of 16 in. strand pullout test specimen

The short-length specimens utilized a 5-in.-outer-diameter steel tube, 1/8-in. wall thickness, and a total length of 12 in. A 6 in. by 6 in. steel plate (3/16-in. thick) was tack-welded to the bottom and the remaining contact surface caulked to prevent any leakage. Within the 12-in.-long steel tube, there was a 9-in. embedment (bond) length with a 2-in. long foam-tape bond breaker at the bottom and a 1-in. long duct tape bond breaker at the top. The top bond breaker extended past the top mortar surface approximately one inch to ensure the exact bond length desired in case of settlement. The strand extended past the top mortar surface approximately two inches. A schematic of the 9-in. pullout specimen is shown in Figure 5.2. The 5-in.-diameter steel tubes were able to be re-used by cutting the tack welds, removing the bottom plate, and pushing out the mortar (with a hydraulic actuator and specially-made frame).

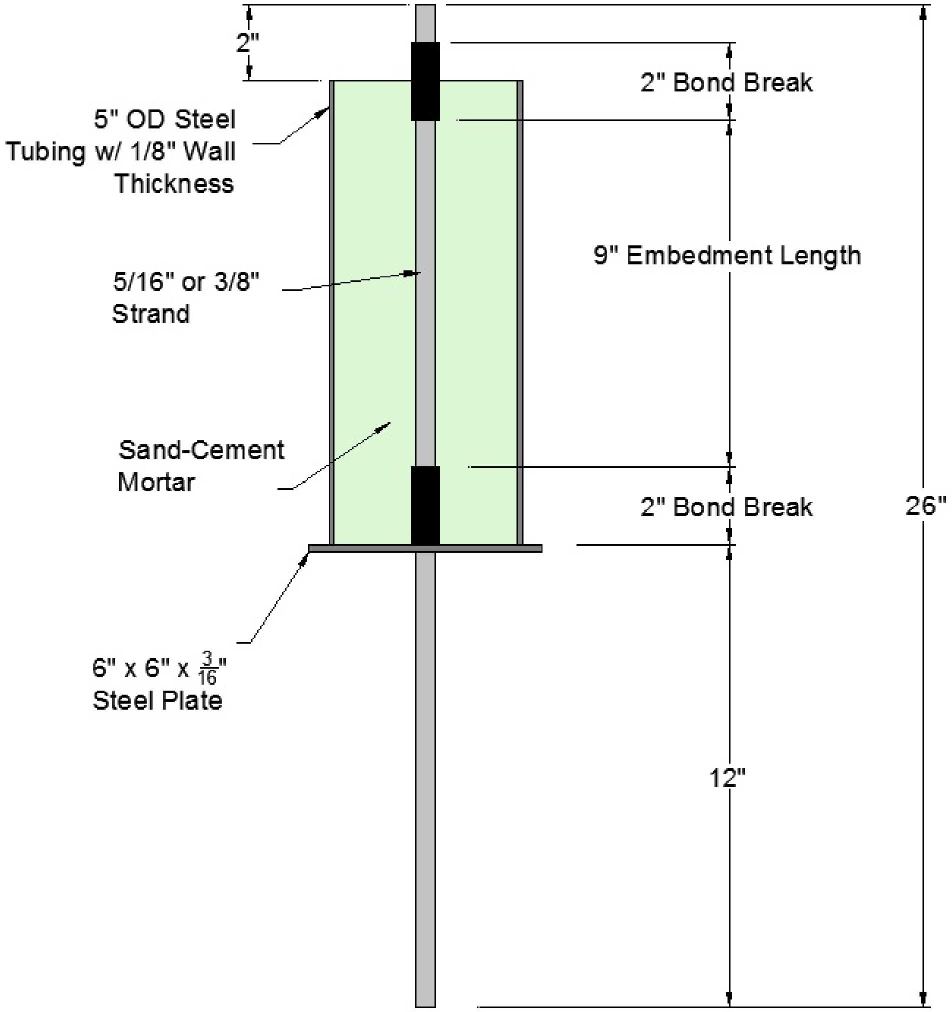


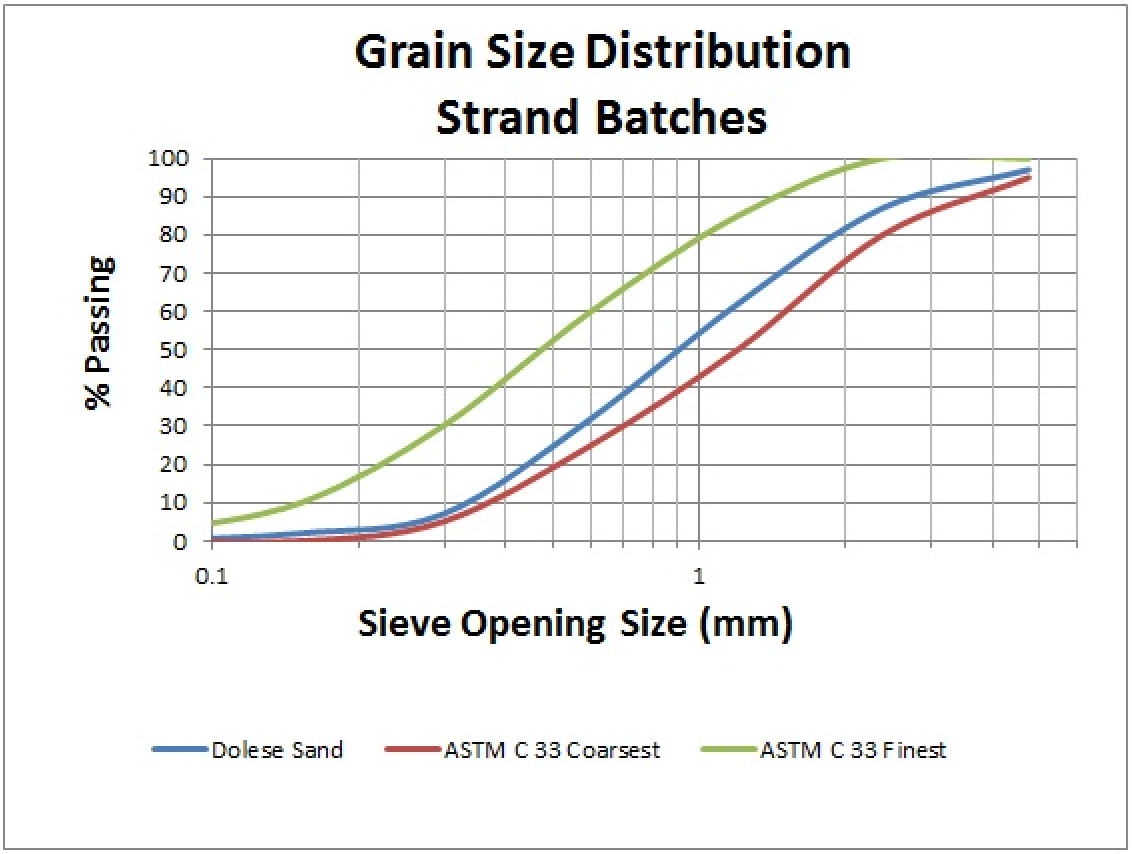
Figure 5.2 Dimensions of 9 in. strand pullout test specimen

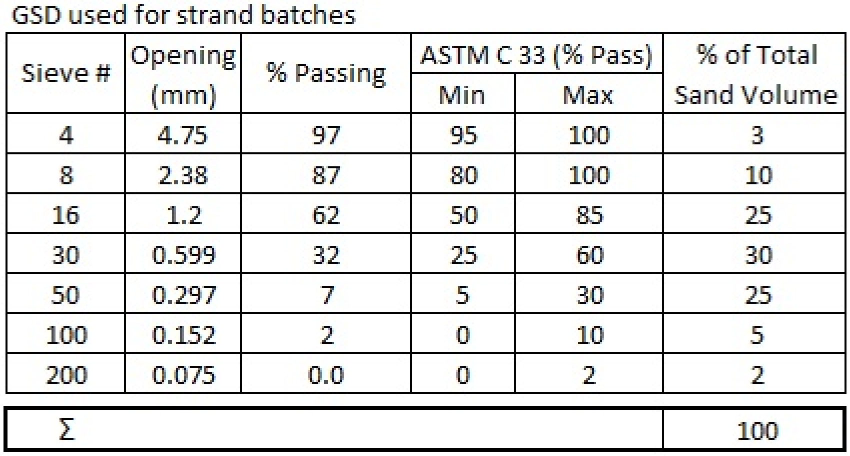
Two different bottom plates were used for the strand specimens. For the 3/8-in.-diameter strands, the bottom plate had a 7/16-in.-diameter hole drilled in the center to allow the steel strand to pass through. For the 5/16-in.-diameter strands, the bottom plate had a 3/8-in.-diameter hole. The strands were held centered in the tube using an additional fixture (shown in Figure 5.3) and rebar ties.

Figure 5.3 Additional fixture used to center strands during casting

5.2.3 Mix Proportions, Material Sources, and Batch Size

A sand-cement mortar mixture was used for all tests. The mix proportions were a water-to-cement ratio (w/c) of 0.46 and a sand-to-cement (s/c) ratio of 2.80. The cement used was a Type III cement from the Monarch Cement Company and it conformed to ASTM C150. The mill certification sheet for this cement can be seen in Appendix P. The sand used was supplied by Dolese Bros. Co., Guthrie, Oklahoma. (Note this is the same sand used to develop the Oklahoma State University portion of the NASP and NCHRP Strand Bond Test protocol.) The sand was sieved and then recombined using the grain-size distribution shown in Figure 5.4 to conform to ASTM C33 and to keep the exact same mortar mix for each batch.




GSD used for strand batches

Sieve #	Opening (mm)	% Passing	ASTM C 33 (% Pass)		% of Total Sand Volume
			Min	Max	
4	4.75	97	95	100	3
8	2.38	87	80	100	10
16	1.2	62	50	85	25
30	0.599	32	25	60	30
50	0.297	7	5	30	25
100	0.152	2	0	10	5
200	0.075	0.0	0	2	2
Σ					100

Figure 5.4 Sand gradation used for strand pullout specimens

For the standard length strand bond test specimens, 2.75 ft^3 of mortar was batched. Each batch was enough to fill 12 strand specimens and 12 mortar cubes with approximately 25 pounds of mortar leftover. For the short-length strand specimens, 1.85 ft^3 of mortar was batched. Each batch was enough to fill 12 strand specimens and 12 mortar cubes with approximately 25 lbf of mortar leftover.

Total batch weights for strand pullout tests can be seen in Table 5.2. This same mixture was used for all strand pullout tests for uniformity. The paddle mixer used can be seen in Figure 5.5.

Table 5.2 Batch weights used for strand pullout specimens

Material	16 in. Specimens Batch Weights (lbf)	9 in. Specimens Batch Weights (lbf)
Oklahoma (Dolese) Sand	254.2	164.3
Monarch Type III Cement	86.8	58.7
Water	40.0	27.0
Total	**381.0**	**250.0**

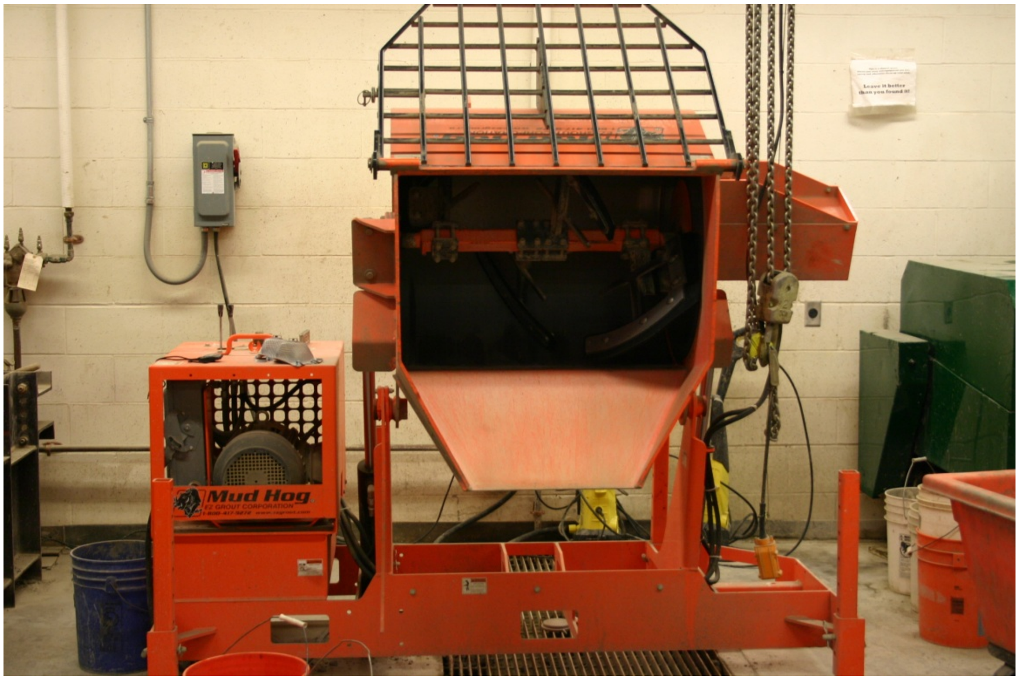


Figure 5.5 Paddle mixer used for strand pullout tests

5.2.4 Specimen Casting and Curing Procedures

Each strand was tested six times and the results averaged. For the 16-in.-diameter strand specimens, a total of six mortar batches were made. Each batch contained 12 pullout specimens, one as-received and one cleaned specimen for each of the six strands. The specimens were cast in six different batches so that any variations due to slight differences in the mortar mixtures would be equally distributed. For the 9-in.-diameter strand specimens, a total of three mortar batches were made. Each batch contained 12 pullout specimens, two as-received specimens for each of the six strands. The mixer used for strand batches was a paddle mixer with a maximum useable capacity of approximately 7.5 ft^3 and can be seen in Figure 5.5.

Mortar for the strand pullout specimens used the following mixing procedure:

1. Place all sieved sand into the paddle mixer and mix for 30 seconds to recombine.
2. Pour approximately 70% of the water into the mixer and mix for 30 seconds.
3. Pour all of cement into the mixer.
4. Start timer while adding remaining water.
5. Mix for three (3) minutes.
6. Turn off mixer. Scrape the mixer for two (2) minutes using trowels, giving special attention to any area that collects dry material.
7. Mix for two (2) minutes.
8. Empty mixer into trough.

Each set of 12 pullout specimens were cast at approximately the same time each day and the temperature in the vicinity of the curing location was maintained at 73.5 ± 3.5 ^{o}F in accordance with ASTM C109. Mortar temperature, room temperature, relative humidity, and mortar flow were recorded directly after the mortar came out of the mixer.

The flow table used for workability testing meets the specifications of ASTM C230 and the flow value is measured using the ASTM C1437 method. A picture of the flow measurement process can be seen in Figure 4.18. Two-in. mortar cubes were made, stored, and tested according to ASTC C109. The pullout specimens were filled in two, approximately equal, lifts and consolidated using a wand-type vibrator between each lift.

After the specimens and mortar cubes were cast, the top surface of each pullout specimen was smoothed using a small trowel and covered for storage (curing). The pullout test specimens and 2-in. mortar cubes were cured by placing a moist cloth over the top surface and covering with plastic. This kept the relative humidity of the specimens and cubes greater than or equal to 90%. The specimens and cubes were then stored in a temperature- and humidity-controlled room, maintained at temperature of 73.5 ± 3.5 ^{o}F and a relative humidity above 50%. Figure 4.19 shows a picture of the moist cloth/plastic covering method used for curing the cubes and Figure 4.20 shows the curing method used for curing the specimens.

Average mortar strength at the time of strand pullout testing (measured from the mortar cubes) and mortar flow value are shown in Table 5.3 for the as-received and cleaned 16-in. strand specimens, and Table 5.4 for the as-received 9-in. strand specimens.

Table 5.3 As-received and cleaned 16 in. strand pullout batch summaries

Mortar Batch Name	Avg. Specimen Cure Time (hrs)	Avg. Cube Strength at Time of Test (psi)	Flow Value
Strand Batch #1	24	4570	122
Strand Batch #2	24	4598	121
Strand Batch #3	24.25	4607	119
Strand Batch #4	23.75	4598	118
Strand Batch #5	23.75	4601	117
Strand Batch #6	24.25	4639	118
Average of Six	**24**	**4602**	**119.2**

Table 5.4 As-received 9 in. strand pullout batch summaries

Mortar Batch Name	Avg. Specimen Cure Time (hrs)	Avg. Cube Strength at Time of Test (psi)	Flow Value
Strand Batch #1	23.75	4632	117
Strand Batch #2	23.25	4663	115
Strand Batch #3	23.5	4669	115.5
Average of Three	**23.5**	**4655**	**115.8**

5.2.5 Testing Procedure

The general testing procedure set forth in Ramirez and Russell (2008) was used for the strand tests presented here. At the time of this testing, no requirement on use of a neoprene rubber pad was in the specifications and this was not used at Kansas State University. Other important testing parameters (such as LVDT setup and data acquisition) are given in the following paragraphs.

Pullout tests were performed shortly after the mortar cube strength reached 4500 psi and ended before the cube strength reached 5000 psi. During testing, the strands were pulled with a displacement rate of 0.1 inch/minute at the bottom, while continuously monitoring and recording the applied load and free-end slip at the opposite (top) end using a linear variable differential transformer (LVDT). This process is shown in Figure 4.21. Depending on size of strand, an appropriate size prestressing chuck was used for the actuator to bear and apply force to the strand. MTS MultiPurpose TestWare 793 software was used to control the servo-hydraulic actuator and also for data acquisition. A more in-depth breakdown of the testing machinery setup and its specifications can be found in Section 4.2.6. Data (time, force and end slip) was collected at every 0.0005 in. of free-end slip using MTS software and hardware.

In the case of seven-wire strands, the LVDT was positioned on the center of the center wire. In the case of the 3-wire strands, the LVDT was positioned on the center of one of the wires. In the case of all three-wire strand test specimens, no wire slipped relative to the other two. If a wire would have slipped relative to the other two, a small piece of metal would have been used to “cap” the strand, and the specimens would have been recast and retested. The LVDT was mounted to the steel tube using two magnetic blocks. A closer view of the LVDT can be seen in the Figure 4.23 setup and the top view of a typical strand specimen is shown in Figure 5.6.

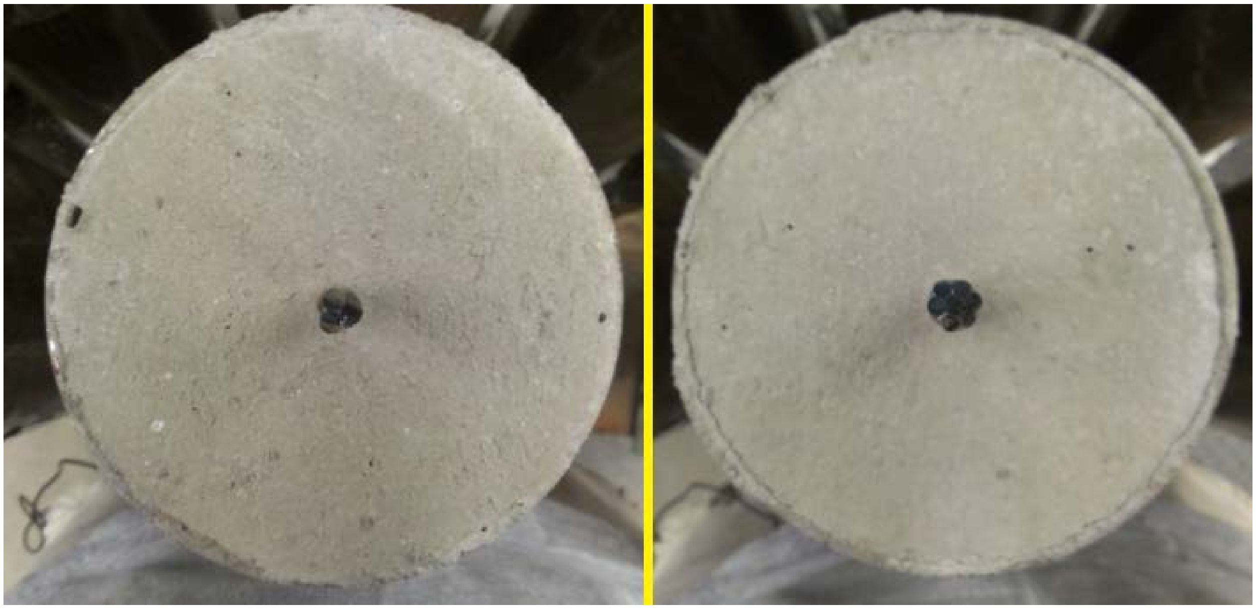


Figure 5.6 Top view of three-wire and seven-wire strand specimens

5.3 Strand Pullout Results and Analysis

Results of the experimental, lab strand testing program are presented in this section. First, results of the “as-received” and “cleaned” pullout specimens are presented in succession. The third section presents transfer length measurements obtained from pre-tensioned prisms. Next, the method of analysis used for strand bond testing is established. Finally, results between the as-received data set and the cleaned data set are compared to distinguish between bond attributed to surface conditions and bond attributed to indent geometry.

5.3.1 As-Received Results

The averaged as-received force vs. end slip results from each strand source and use of standard length strand specimens (bond length equal to 16 in.) are presented in Figure 5.7. The average force at each increment of end slip (0.0005 in.) was obtained by arithmetically adding the force results from each of the six individual specimens and then dividing by six. The same process was used to average the end slip measurements for each strand group.

Each line on the graph represents the average of six individual specimens from the same strand source. Each of the six specimens was cast in a different batch of mortar. The force vs. end slip graphs, showing individual results of the six specimens for each strand source, can be seen in Appendix K.

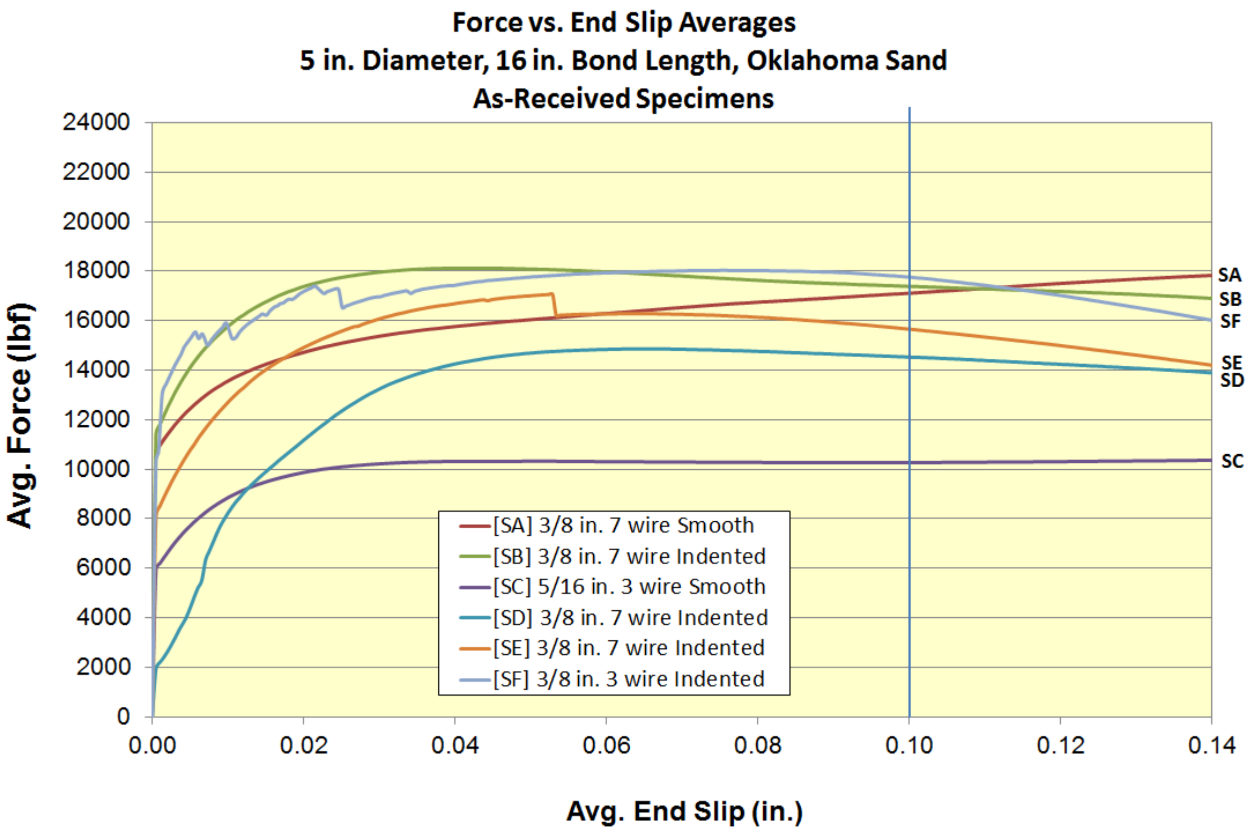


Figure 5.7 As-received strand force vs. end slip averages (16 in. bond length)

From Figure 5.7, it is clear the 16-in. bond length is too long for the higher bonding strands. With this long of a bond length, specimens containing strands SE and SF had to be stopped early during testing for fear of steel rupture failure prior to bond pullout failure. This is represented graphically by the sudden jumps in the graph as one of the high bonding specimens drops out of the data set. The specimens needed to be shortened to accommodate these higher bonding strands. With this goal in mind, a modified specimen size utilizing a 9-in. bond length was proposed for smaller diameter (less than or equal to 0.5 in.) strands by the researchers. No other parameters to the specimen size or testing protocol were changed from the standard strand bond test (Ramirez and Russell, 2008).

Figure 5.8 shows the average as-received force vs. end slip results of the shortened length strand specimens (bond length equal to 9 in.). Each line on the graph represents the average of six individual specimens from the same strand source. Each of the six specimens was cast in a different batch of mortar. The force vs. end slip graphs, showing the individual results of the six specimens for each strand source, can be seen in Appendix K.

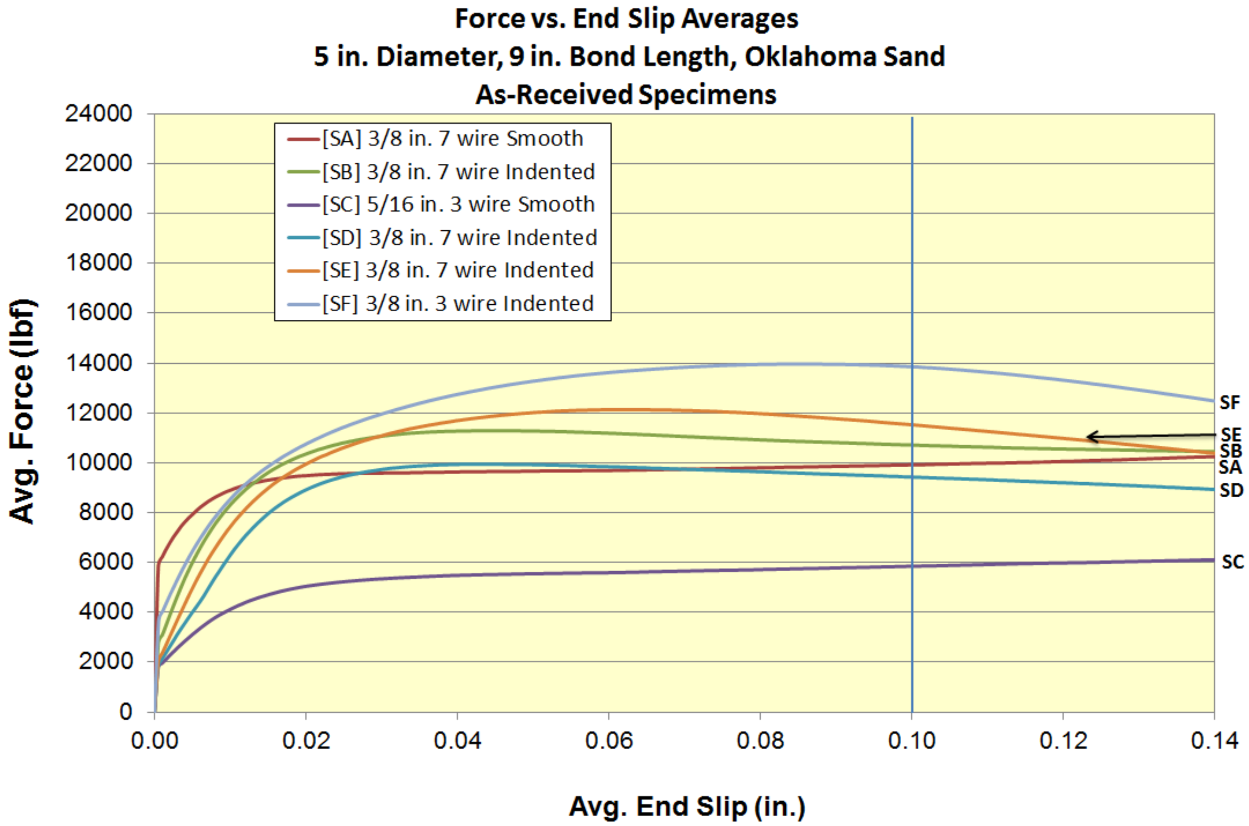


Figure 5.8 As-received strand force vs. end slip averages (9 in. bond length)

5.3.2 Cleaned Results

The averaged cleaned force vs. end slip results from each strand source and use of standard length strand specimens (bond length equal to 16 in.) is presented in Figure 5.9. The average force at each increment of end slip (0.0005 in.) was obtained by arithmetically adding the force results from each of the six individual specimens and then dividing by six. The same process was used to average the end slip measurements for each strand group.

Each line on the graph represents the average of six individual specimens from the same strand source. Each of the six specimens was cast in a different batch of mortar. The force vs. end slip graphs, showing individual results of the six specimens for each strand source, can be seen in Appendix K.

From Figure 5.9, it is clear the 16-in. bond length is too long for the higher bonding strands. This was the same trend represented in the as-received strand specimens. With this long of a bond length, specimens containing strands SB, SE, and SF had to be stopped early during testing for fear of steel rupture failure prior to bond pullout failure. This is represented graphically by the sudden jumps in the graph as one of the high-bonding specimens drops out of the data set.

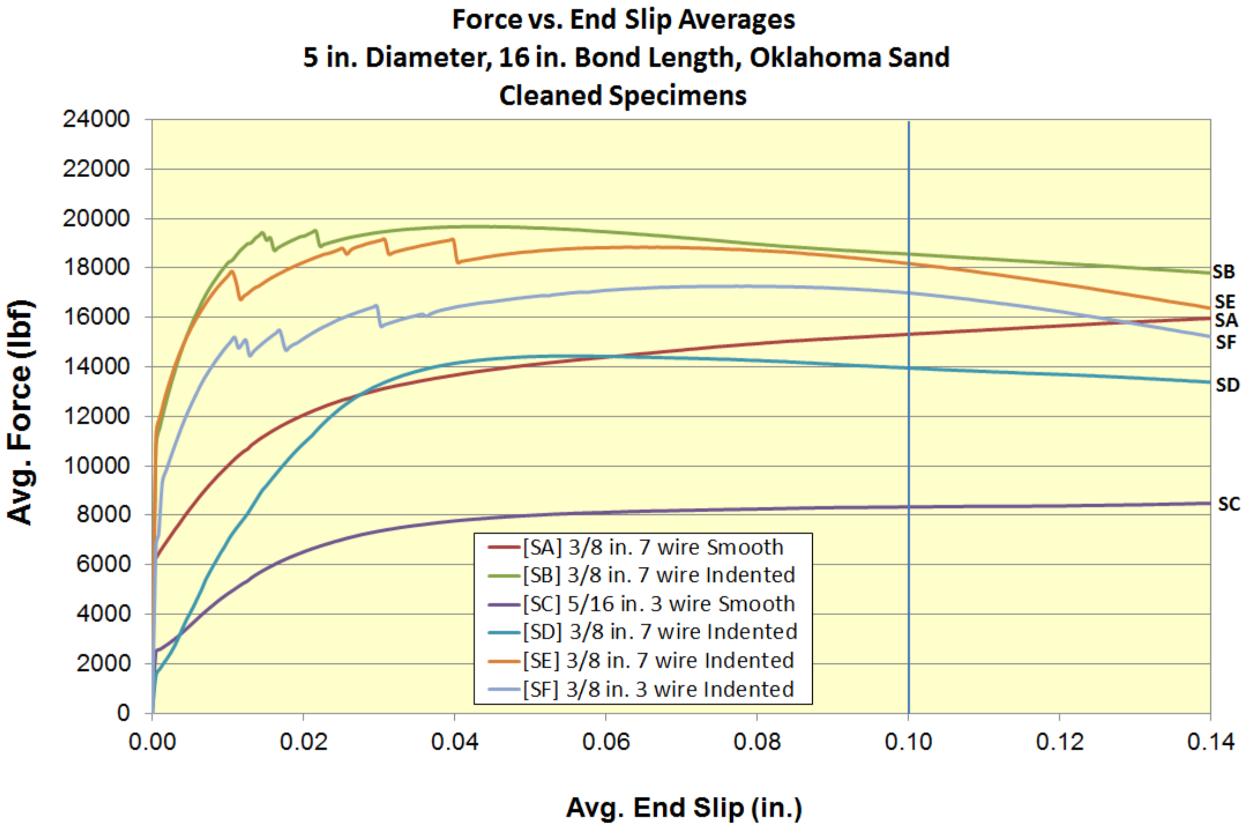


Figure 5.9 Cleaned strand force vs. end slip averages (16 in. bond length)

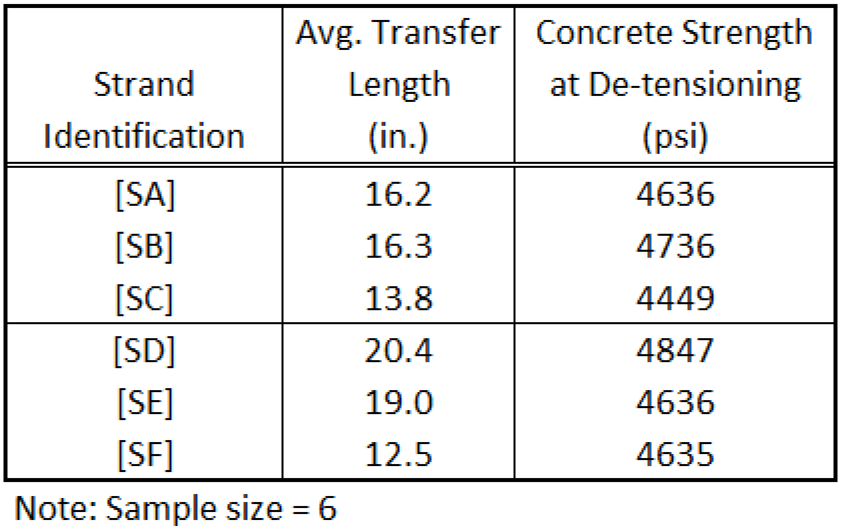
5.3.3 Transfer Length Data

Data presented in Table 5.5 shows the average strand transfer length measurements determined from the surface strain data obtained by the KSU research team. Transfer lengths were determined from the surface strain data obtained from accompanying pre-tensioned prisms using the same strands as the pullout tests. Surface strain data was obtained for the entire length of the prisms. A bilinear strain profile was assumed for the software that calculated the transfer lengths.

The strands used for the pre-tensioned prisms were stored and preserved along with the strands used for the pullout tests. Three pre-tensioned prisms were cast using each strand. A transfer length was measured from each member end, resulting in a total of six transfer lengths (six data points).

Prisms were cast with four strands in a square pattern and were meant to be as representative as possible of actual concrete railroad ties. The concrete-to-steel-wire area of each prism is approximately the same as that of a typical concrete railroad tie produced in the United States. These prisms were cast using a concrete mixture similar to one used in a major concrete tie manufacturing plant in the United States. This mixture utilized the same coarse aggregate sources, mix proportions, and admixtures as the manufacturing plant. The prisms were de-tensioned at approximately 4500 psi (the same strength of the mortar used for pullout testing). Actual strength of the concrete at the time of de-tensioning for each batch can be seen in Table 5.5. The batching and testing procedures used to obtain the transfer lengths from these pre-tensioned prisms are presented in Bodapati's 2013 paper, but are not discussed here.

Table 5.5 Strand transfer length data



Strand Identification	Avg. Transfer Length (in.)	Concrete Strength at De-tensioning (psi)
[SA]	16.2	4636
[SB]	16.3	4736
[SC]	13.8	4449
[SD]	20.4	4847
[SE]	19.0	4636
[SF]	12.5	4635

Note: Sample size = 6

5.3.4 Analysis

All methods of analysis in this section compared results from Section 5.3.1 (as-received strand pullout data) to results from Section 5.3.3 (strand transfer length data).

This experimental program analyzed the strand pullout data by recording the force at 0.10 in. of free end slip. This method of analysis is laid out in the NASP (Russell, 2006) and NCHRP 603 (Ramirez and Russell, 2008) reports. Due to the large amount of previous research done on prestressing strand bond, no other method of analysis was looked into. The analysis done in this section is provided to give evidence of support or refutation of the modified bond length for strands of smaller diameter (less than 0.5-in. diameter).

The correlation was found for 1) all six wires, and 2) for only the five strands with 3/8-in.-diameter. This was done because the transfer lengths obtained from the prisms using 5/16-in.-diameter strands (SC) used different cross-sectional dimensions.

For clarification, the x-coordinate (abscissa) of each point in these graphs represents the average of six transfer length readings; the y-coordinate (ordinate) of each point in these graphs represents the average of six individual pullout tests required to cause 0.10 in. of free end slip. The R^2 is the correlation between these two averaged data sets. Further discussion on strand SC is given below.

For the standard length specimens (16-in. bond length), the pullout force at 0.10 in. of end slip, compared with the average transfer length, can be seen in Table 5.6 and Figure 5.10. For the modified-length specimens (9-in. bond length), the pullout force at 0.10 in. of end slip, compared with the average transfer length, can be seen in Table 5.7 and Figure 5.11. Both Figure 5.10 and Figure 5.11 show the results of the data set including all six strands and the data set including only the 3/8-in.-diameter strands (five strands).

When considering all six strands, the data sets for the 16-in. and 9-in. bond length specimens give R^2 values both less that 0.005 from Figure 5.10 and Figure 5.11. Both of these values show no statistical correlation between the pullout forces and measured transfer lengths. When looking for the source of these results, it became clear strand SC was an outlier. A few ideas as to why the prisms containing strand SC was an outlier have been discussed, but no proof can be given to support any of the claims. Regardless, it is clear something affected the test making SC an outlier.

When repeating the same analysis using only the five 3/8-in.-diameter strands, the data sets for the 16-in. and 9-in. bond length specimens give R^2 values of 0.852 and 0.573, respectively, from Figure 5.10 and Figure 5.11. These values shown a decent-to-good correlation between pullout forces and measured transfer lengths of 3/8-in.-diameter strands. If one data point (SC) can change the statistical correlation in such an extreme manner, it is hard to draw conclusions concerning these results.

Table 5.6 As-received strands, pullout force at 0.10 in. end slip (16 in. bond length)

Strand Bond Test Results
5 in. Diameter, 16 in. Bond Length, Oklahoma Sand
Pullout Force at 0.10 in. End Slip

Strand	Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[SA]	17105	1032	6.0	16.2
[SB]	17388	1396	8.0	16.3
[SC]	10267	1958	19.1	13.8
[SD]	14532	782	5.4	20.4
[SE]	15667	987	6.3	19.0
[SF]	17767	0	0.0	12.5

Note: Sample Size = 6, E = 5, F = 1

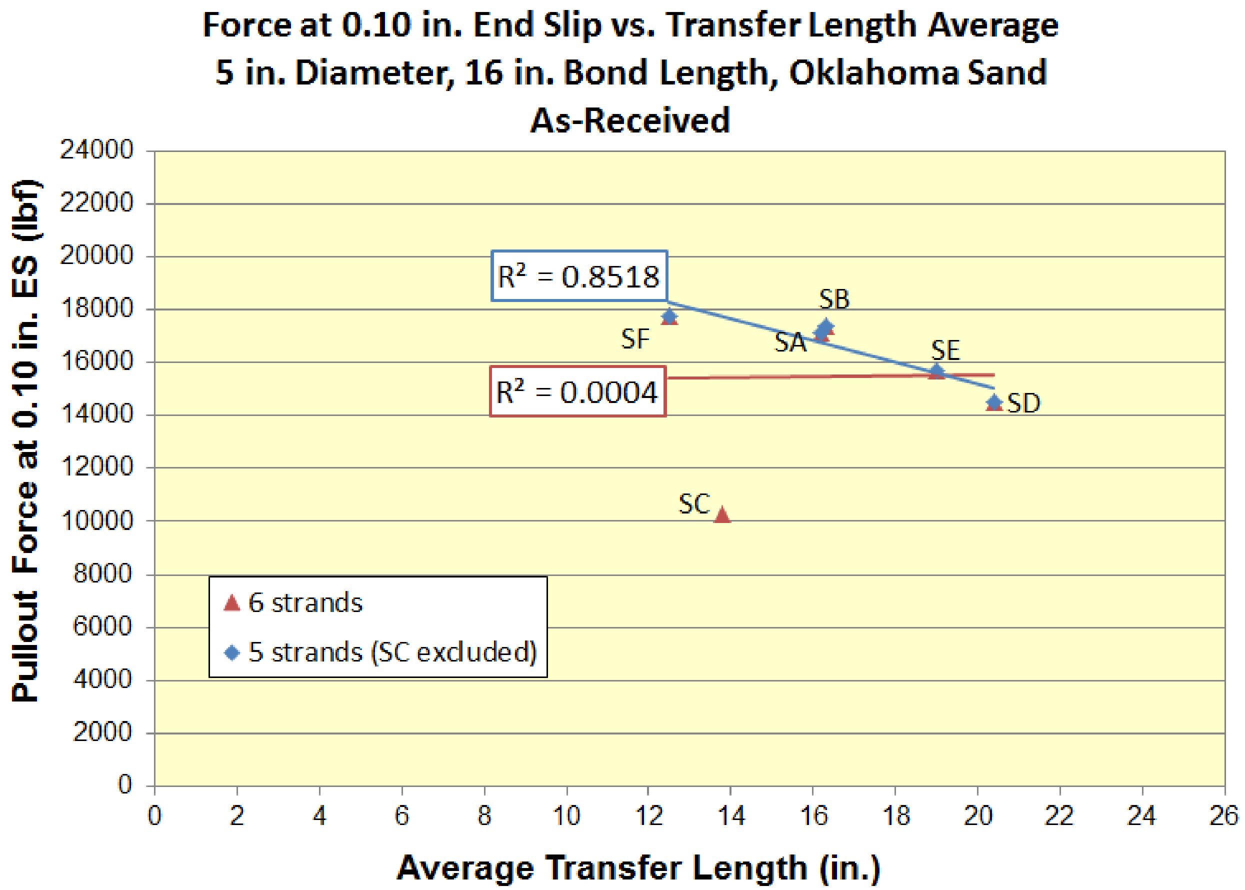
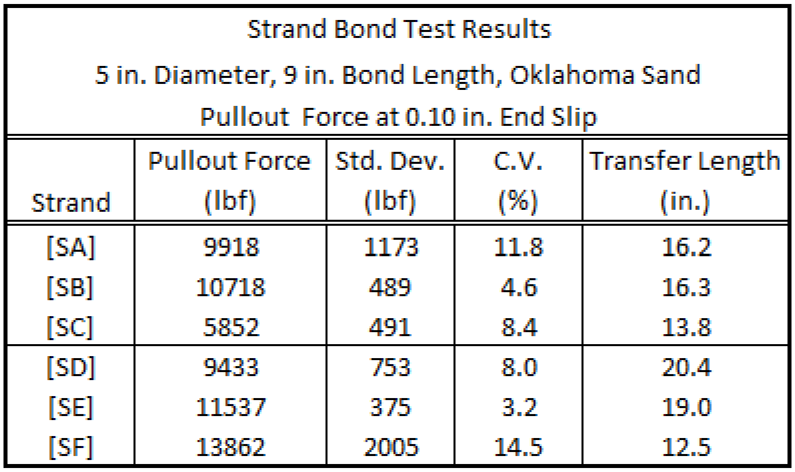


Figure 5.10 As-received strands, pullout force at 0.10 in. end slip (16 in. bond length)

Table 5.7 As-received strands, pullout force at 0.10 in. end slip (9 in. bond length)


Strand Bond Test Results
5 in. Diameter, 9 in. Bond Length, Oklahoma Sand
Pullout Force at 0.10 in. End Slip

Strand	Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[SA]	9918	1173	11.8	16.2
[SB]	10718	489	4.6	16.3
[SC]	5852	491	8.4	13.8
[SD]	9433	753	8.0	20.4
[SE]	11537	375	3.2	19.0
[SF]	13862	2005	14.5	12.5

Note: Sample Size = 6

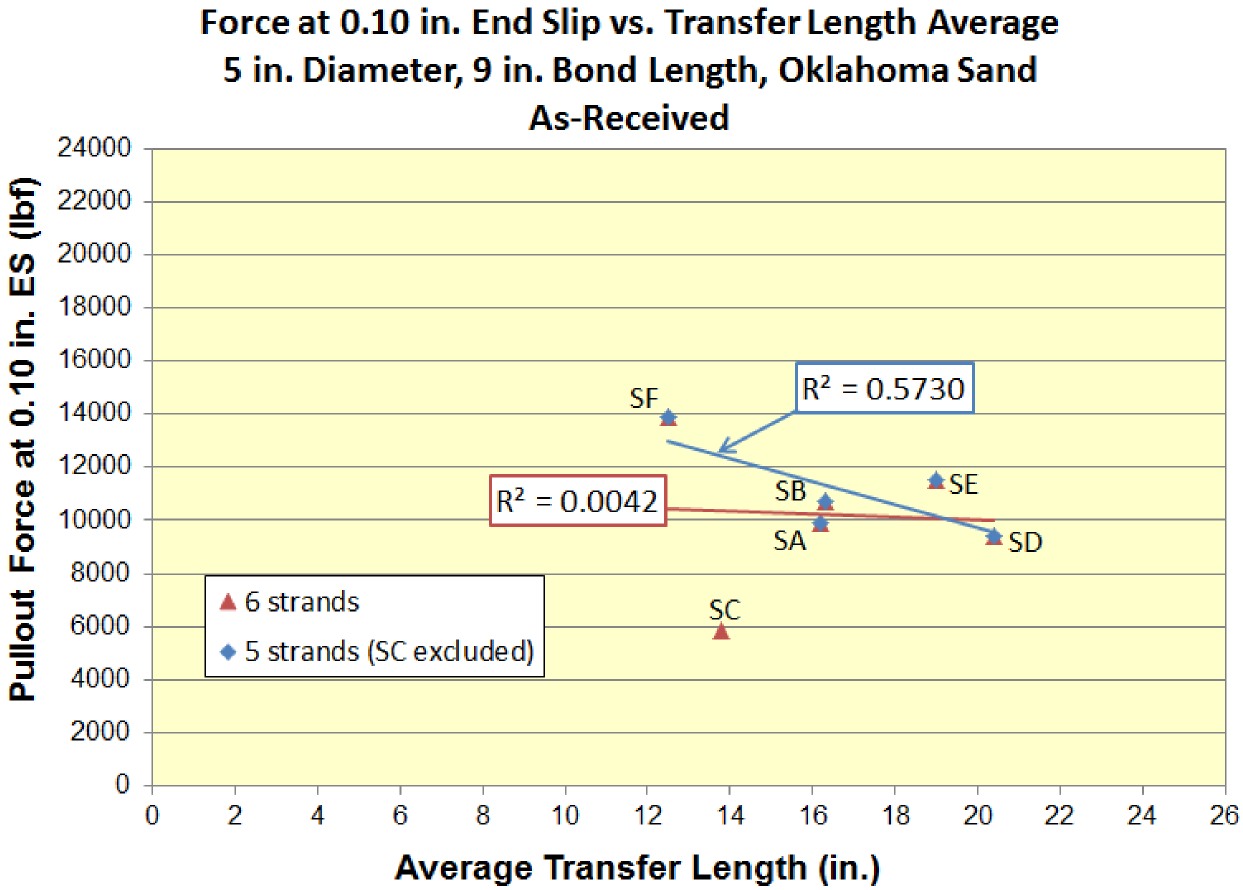


Figure 5.11 As-received strands, pullout force at 0.10 in. end slip (9 in. bond length)

5.3.5 Comparison of As-Received vs. Cleaned

The analysis in this section compared results from Section 5.3.1 (as-received strand pullout data) to results from Section 5.3.2 (cleaned strand pullout data). This section directly compares results of as-received and cleaned strand specimens. This issue focuses on differentiating between bond associated with indent geometry and bond associated with surface condition.

All six strands (SA, SB, SC, SD, SE, and SF) were tested both in their as-received and cleaned conditions using the standard strand bond test (16-in. bond length). Of these strands, SA and SC exhibited slight to moderate levels of rusting. Strand SD appeared to have a slight residue coating the surface, possibly drawing lubricants from manufacturing or some other form of light grease or oil. The remaining three strands (SB, SE, and SF) appeared to have no noticeable signs of either rust or oils. Due to these different surface conditions, it was hypothesized that strands SA and SC would perform slightly worse after being cleaned due to having the rust removed. Slight rusting has been shown to improve bond performance during similar testing done on strands (Gustavson, 2004; Rose and Russell, 1997; Barnes, Grove, and Burns, 2003). Similarly, it was originally thought strand SD would exhibit better bond after being cleaned due to having the oil removed. It was assumed the remaining three strands would show roughly the same bond performance before and after the cleaning process.

Average pullout force vs. end slip graph for each strand is shown in Figure 5.12 through Figure 5.17. Each “as-received” and “cleaned” line on the graphs represents the six averaged specimens for those respective tests. Results of the individual pullout tests comparing six as-received specimens to six cleaned specimens can be seen in Appendix L.

From Figure 5.12 through Figure 5.17, it can be seen fairly definitively that four of the six strands (SA, SB, SC, and SE) performed much differently before and after the cleaning process. Strand SA performed worse after the cleaning process, which was anticipated due to the moderate rusting being removed. The bond performance of SB increased considerably after the cleaning process to the point that three of the six tests had to be stopped for fear of the steel strands rupturing instead of pullout bond failure. Similar to SA, the bond performance of SC decreased noticeably after the rust was removed from the surface through the cleaning process. This was expected. Strand SE had a noticeably higher bond capacity after the cleaning process as shown in Figure 5.16. This point is further illustrated in Appendix L by four of the six cleaned wires having to be stopped prior to pullout failure for fear of material rupture.

The remaining two strands (SD and SF) either performed the same before and after cleaning – as was the case with SD – or gave non-definitive results – as was the case with SF. Strand SD produced nearly the exact same force vs. end slip curve in its as-received and cleaned surface condition. This result can be seen in Figure 5.15. This was somewhat surprising given the oily nature of the strand’s surface when it arrived at Kansas State University. The results of strand SF were not able to be fully analyzed because five of the six as-received specimens and four of the six cleaned specimens had to be stopped prior to pullout bond failure due to fear of material rupture (reaching the ultimate stress). This result can be seen in Appendix L. Despite stopping the test early, results of SF still appeared to show relatively similar bond performance before and after cleaning, which was the anticipated result. However, further testing would need to be done to confirm this theorem.

While it is not fully known why strands SD and SF exhibited similar bond performance before and after the cleaning process, the general trend for this portion of the strand analysis led to the conclusion that surface condition of prestressing strands does have a noticeable effect on bond performance. This phenomenon was exhibited in four of the six strand sources with all variations represented. Of these smaller diameter strands affected by the surface condition, two were indented, two were not indented, one was three-wire, and three were seven-wire. This conclusion makes sense when the overall geometry of the strand is considered. Since the area of the strand indents is small relative to the overall cross-sectional area of the 5/16-in.-diameter and 3/8-in.-diameter strands, then it makes sense the indent geometry would play a small role in overall bond performance of the strands and surface condition would contribute a much more meaningful portion.

This seems to also explain why strand SA (3/8-in.-diameter seven-wire, smooth) performed better than strand SB (3/8-in.-diameter seven-wire, indented) before the cleaning process, but performed worse after SB after the cleaning process. Strands SA and SB are from the same steel manufacturer. Logic indicates the indented strand, SB, would exhibit higher bond quality than the smooth strand, SA, if the surface conditions were the same. This proved to be true after the cleaning process. Once the rust was removed from SA, it performed noticeably worse than SB after cleaning, which had previously exhibited no rust. Prior to cleaning, SA and

SB had performed almost identically for both 16-in. and 9-in. bond lengths as can be seen in Figure 5.7 and Figure 5.8.

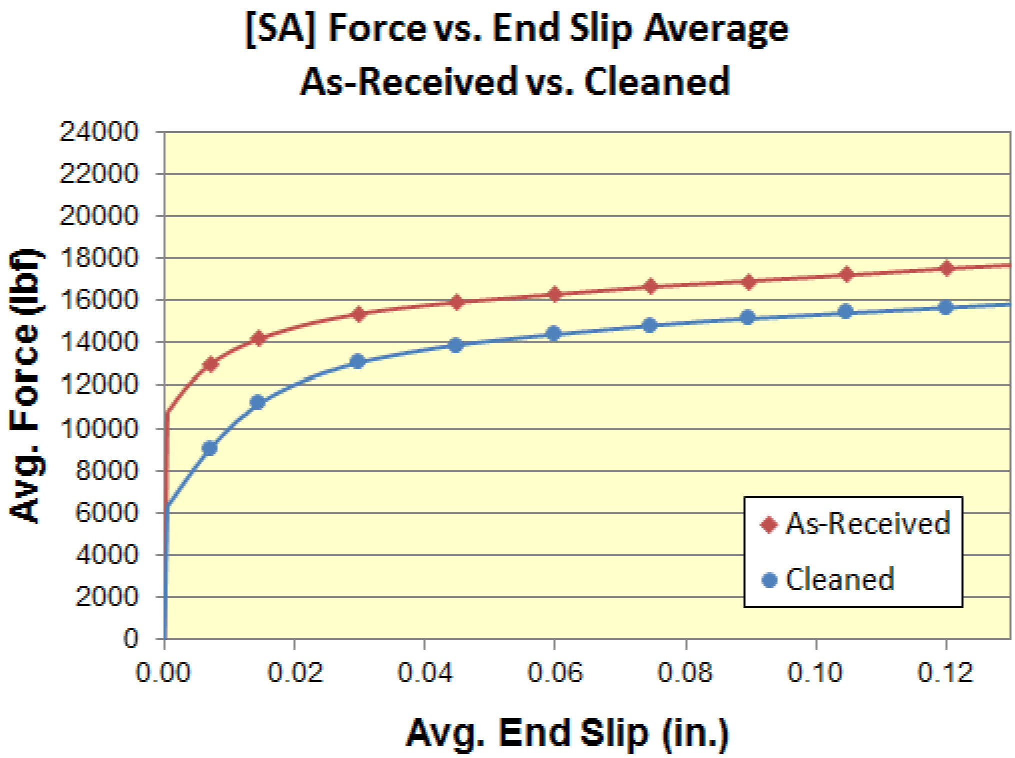


Figure 5.12 [SA] force vs. end slip average graphs, as-received vs. cleaned

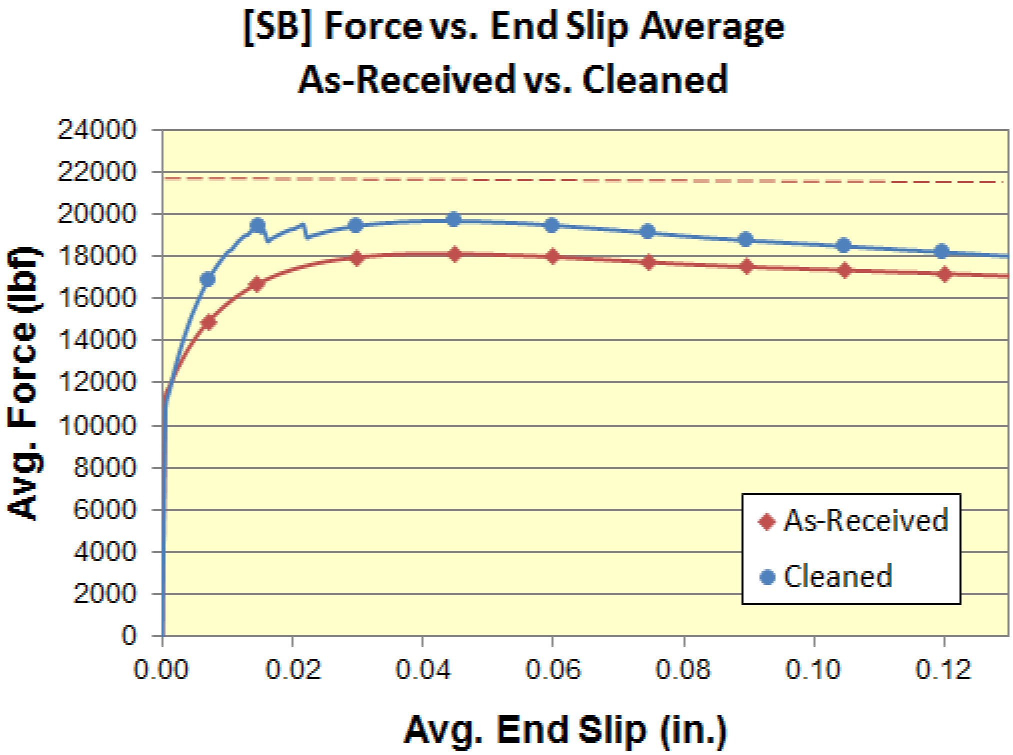


Figure 5.13 [SB] force vs. end slip average graphs, as-received vs. cleaned

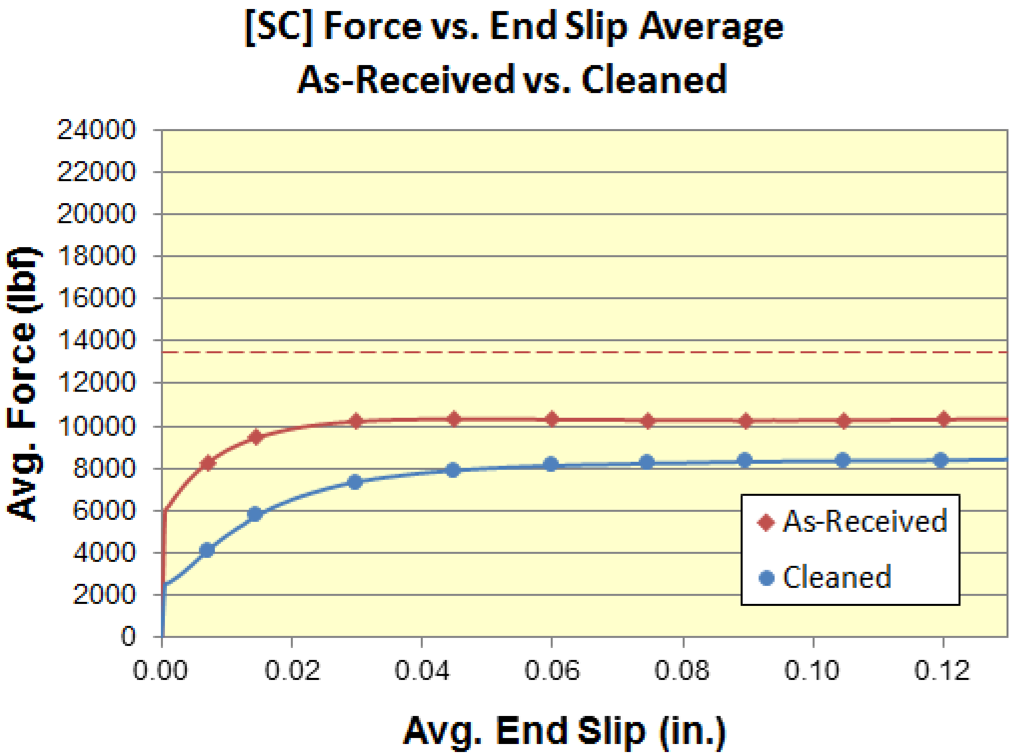


Figure 5.14 [SC] force vs. end slip average graphs, as-received vs. cleaned

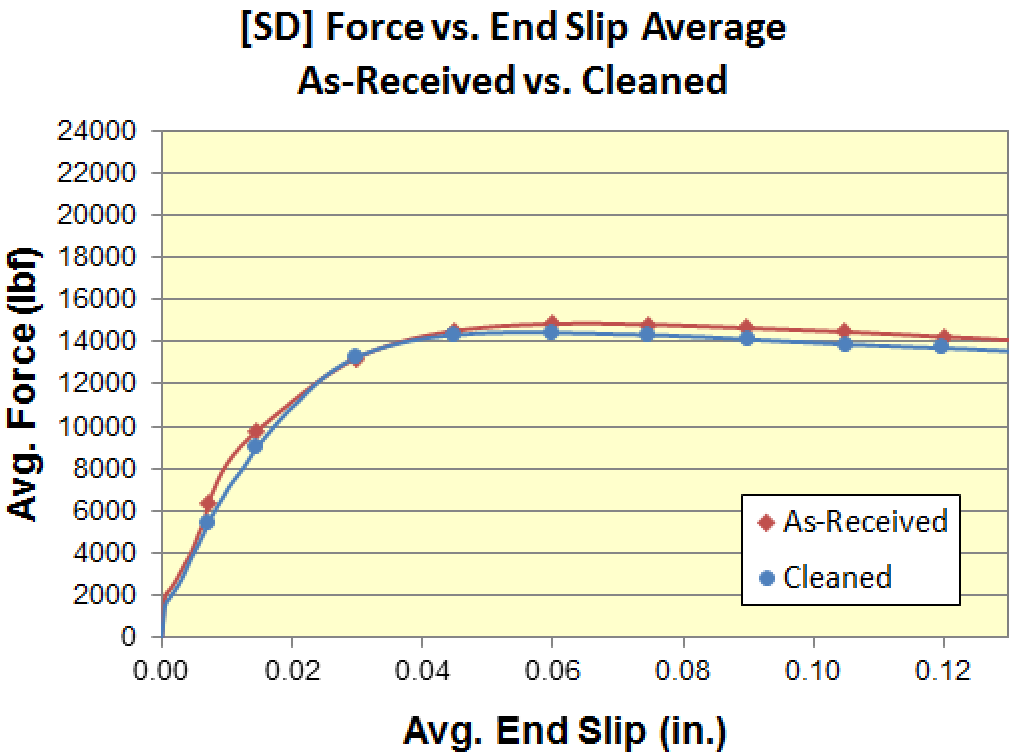


Figure 5.15 [SD] force vs. end slip average graphs, as-received vs. cleaned

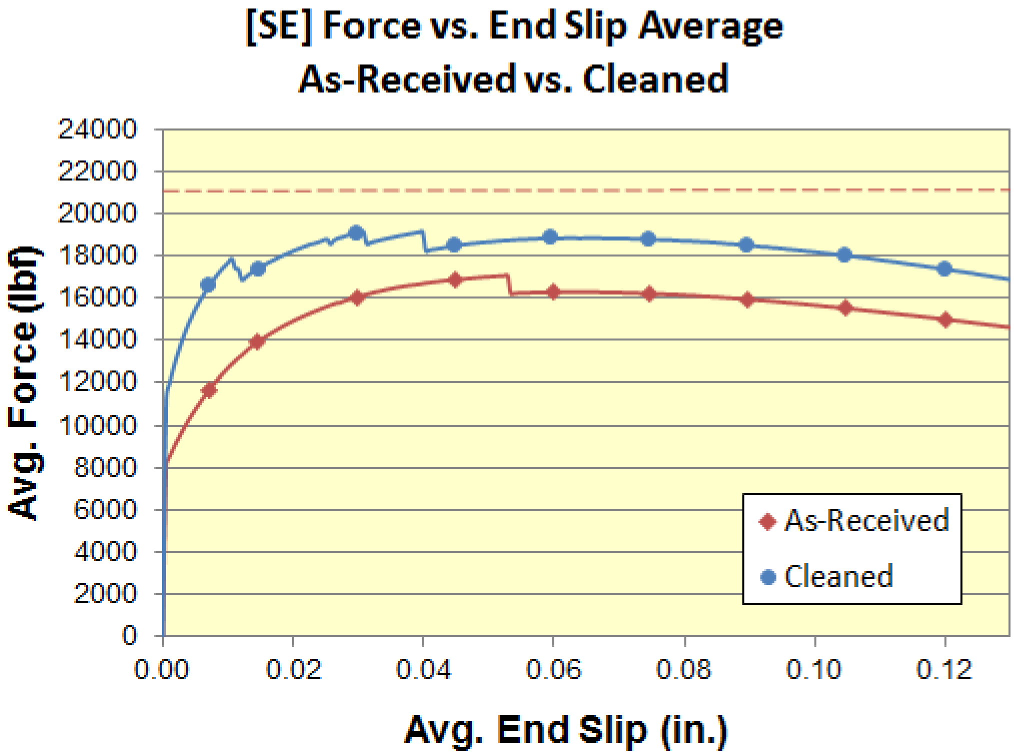


Figure 5.16 [SE] force vs. end slip average graphs, as-received vs. cleaned

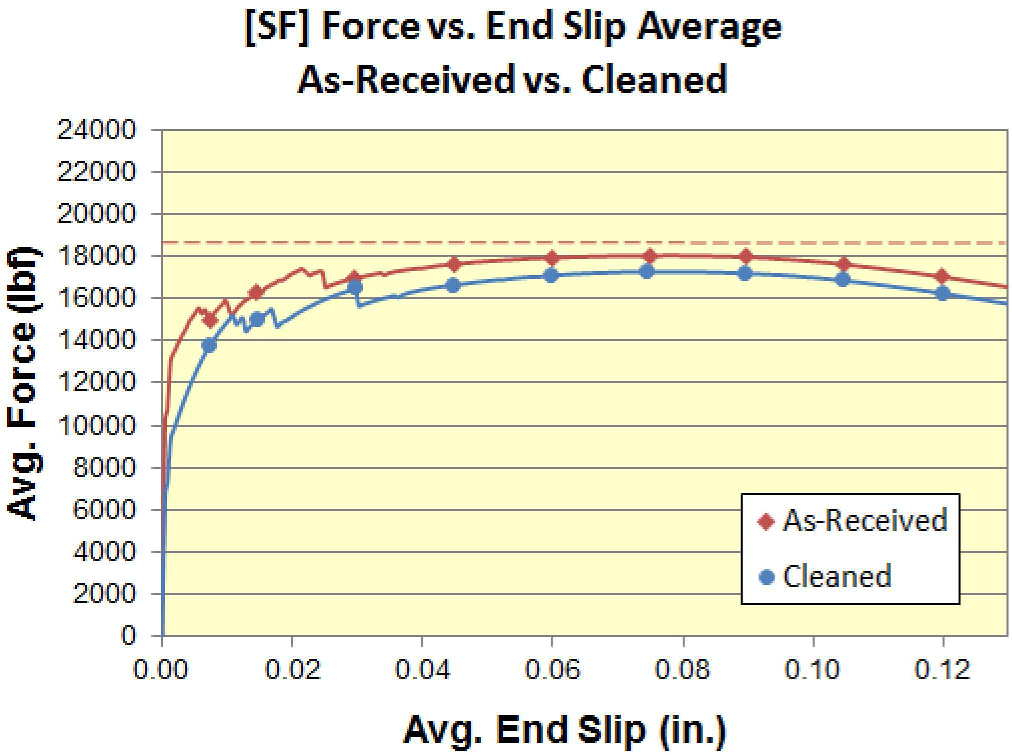


Figure 5.17 [SF] force vs. end slip average graphs, as-received vs. cleaned

Chapter 6 - Plant Phase; Wire and Strand Pullout Testing (Un-tensioned Tests in Concrete)

Chapter 6 discusses the experimental program, results, and analysis of the plant portion of the wire and strand bond pullout tests. These tests are un-tensioned and were performed in concrete. The plant phase refers to the research team from Kansas State University (KSU) going to CXT Concrete Ties (CXT) in Tucson, Ariz. to measure transfer lengths in actual, non-prismatic concrete railroad ties. Pullout specimens were cast to accompany the transfer lengths taken from the railroad ties. Fifteen reinforcements from seven different steel manufacturers were used in the plant phase, and were the same as the reinforcements used for pullout and transfer length tests at KSU. Approximately fifty transfer length measurements and six pullout specimens were obtained for each reinforcement type. Table 6.1 shows the testing matrix of all wires and strands used for the plant testing phase.

Table 6.1 Testing matrix of plant phase

	Reinforcement Manufacturer	Reinforcement Identification	Indentation Type	Number of test specimens	
				Transfer lengths (no. of ends)	As-received un-tensioned pullouts
Wires	A	[WA]	Smooth	49	4
	A	[WB]	Chevron	50	5
	A	[WC]	Spiral	47	4
	B	[WD]	Chevron	49	6
	B	[WE]	Spiral	48	6
	B	[WF]	Diamond	49	6
	C	[WG]	Chevron	49	6
	D	[WH]	Chevron	50	6
	E	[WI]	Chevron	50	6
	E	[WJ]	Chevron	47	6
	F	[WK]	4-Dot		
	F	[WL]	2-Dot	47	6
	G	[WM]	Chevron	49	6
	Wires Total:			**584**	**67**
Strands	A	[SA]	3/8" 7-Wire, Smooth	45	6
	A	[SB]	3/8" 7-Wire, Indented	50	6
	A	[SC]	5/16" 3-Wire, Smooth	48	4
	Strands Total:			**143**	**16**

6.1 General Testing Protocol

The general testing protocol used for pullout testing at CXT was the same as the methodology developed at KSU. A 4-in.-diameter by 8-in.-long steel cylinder mold was used to cast the specimens. The steel reinforcement was held centered in the molds using an external fixture similar to the ones used at KSU. Minor differences between the two protocols are listed below.

Concrete was used for the CXT pullout tests instead of the sand-cement mortar used at KSU. The concrete used for pullout testing came from the same batches as the concrete used to pour the railroad ties. The CXT pullout specimens were consolidated in two lifts using a vibrating table instead of the wand-type concrete vibrator used to consolidate the mortar at KSU. A slump test using a slump cone was done to measure the workability of the concrete rather than the flow table measurement used for the mortar at KSU. The concrete strength at CXT was measured by casting 12 4-in. x 8-in. cylinders instead of the 2-in. mortar cubes used for testing mortar strength at KSU.

The specimens were stored in a temperature-controlled room at approximately 150 ^{o}F, which allowed the specimens and strength cylinders to heat up similar to the concrete railroad ties themselves. A force controlled test was run by manually controlling the flow rate of a small hydraulic pump. This pump was not servo-controlled as was the setup at KSU. The force was applied at the bottom, and the end slip was continuously measured and recorded at the top using an LVDT. This is the same process used at KSU.

6.2 Experimental Program

This section contains information used for this experimental testing program regarding pullout bond tests using steel prestressing wires and strands in a plant environment. Information includes specimen dimensions; mix proportions, material sources, and match sizes; specimen casting and storage procedures; and testing procedures used while performing pullout tests at a concrete railroad tie plant.

6.2.1 Specimen Dimensions

Two specimen sizes were used for the pullout testing portion of the plant phase, one for wire specimens and one for strand specimens. Both specimens were the exact same size except for the bond length used. The wire specimens utilized a 6-in. bond length and the strand specimens utilized a 4-in. bond length.

The wire specimens utilized a 4-in.-inner-diameter steel splitting cylinder mold, 1/4-in. wall thickness, and a total length of 8 in. A 6-in. by 6-in. steel plate (1/4-in. thick) was held fixed to the bottom using two wing nuts. Within the 8-in.-long steel mold, there was a 6-in. embedment (bond) length with a 2-in. long duct tape bond breaker at the bottom of the wire specimens. The wire extended past the top concrete surface approximately two inches. A schematic of the CXT wire pullout specimen is shown in Figure 6.1. The bottom plate had a 1/4-in.-diameter hole drilled in the center to allow the steel wire to pass through. The wires were held centered in the cylinder mold using an additional fixture (shown in Figure 6.3).

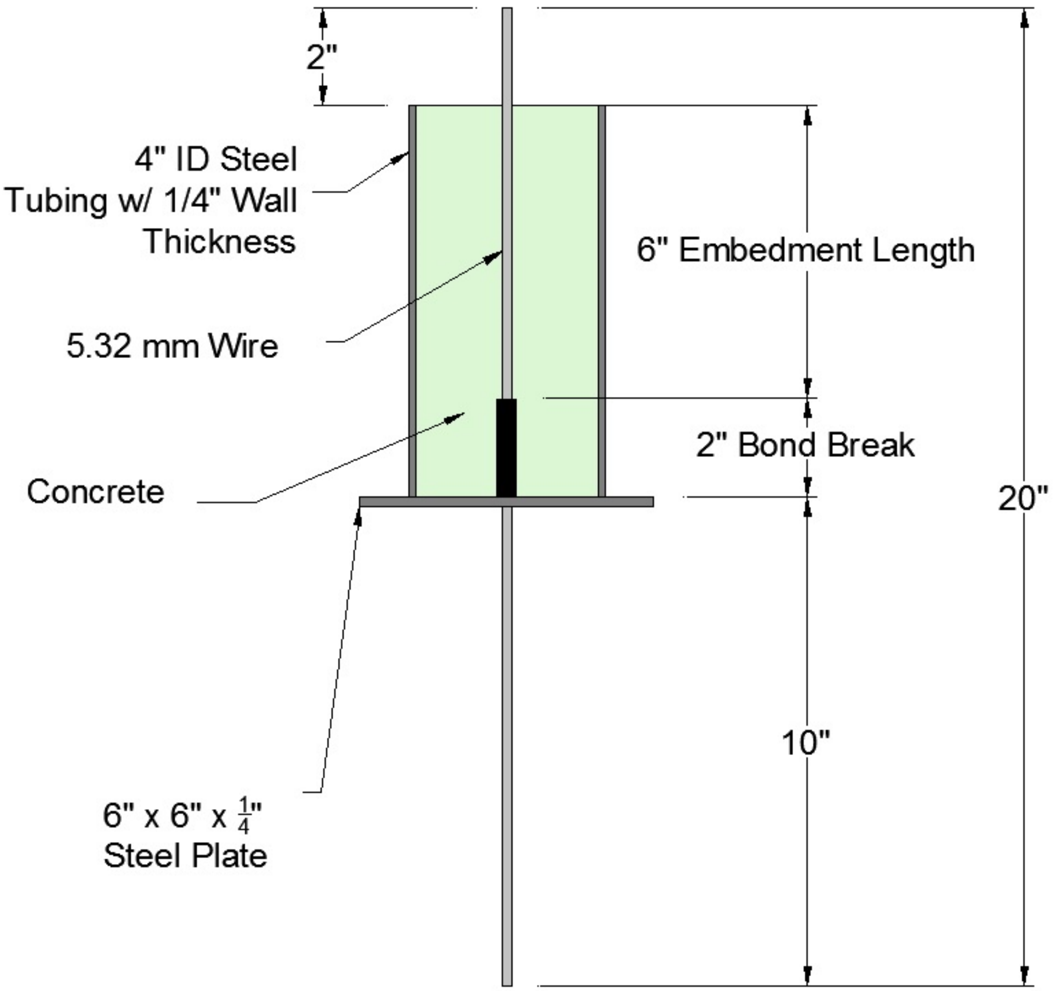


Figure 6.1 Dimensions of wire pullout test specimen at CXT

The strand specimens utilized a 4-in.-inner-diameter steel splitting cylinder mold, 1/4-in. wall thickness, and a total length of 8 in. A 6-in. by 6-in. steel plate (1/4-in. thick) was held fixed to the bottom using two wing nuts. Within the 8-in.-long steel mold, there was a 4-in. embedment (bond) length with a 4-in. long duct tape bond breaker at the bottom of the strand specimens. The strand extended past the top concrete surface approximately two inches. A schematic of the CXT strand pullout specimen is shown in Figure 6.2. The bottom plate had a 1/4-in.-diameter hole drilled in the center to allow the steel wire to pass through. The strands were held centered in the cylinder mold using an additional fixture (similar to the one shown in Figure 6.3).

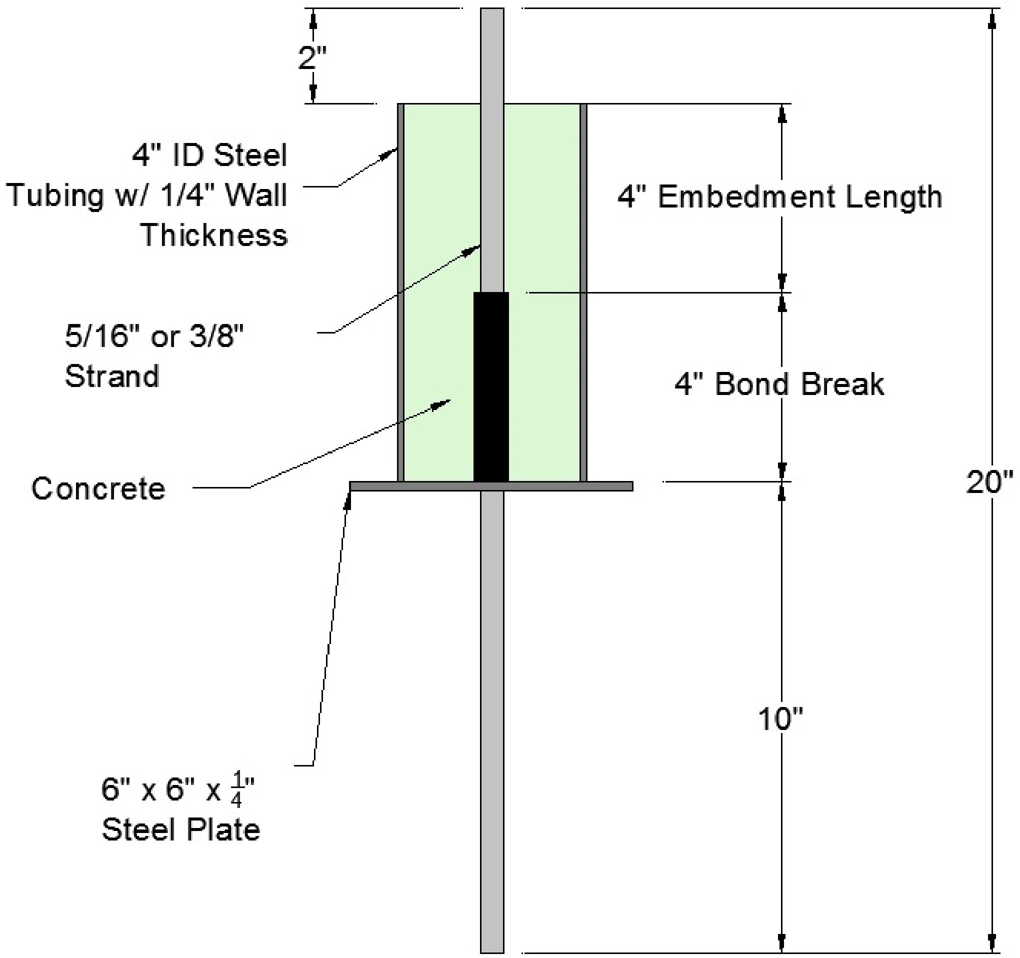


Figure 6.2 Dimensions of strand pullout test specimen at CXT

Figure 6.3 Additional fixture used to center reinforcement during casting at CXT

6.2.2 Mix Proportions, Material Sources, and Batch Size

The 15 reinforcements were cast on 10 separate days using 10 separate concrete batches. The batches had water-to-cement (w/c) ratios typical of most concrete railroad tie plants in the United States. The cement used was a Type III cement conforming to ASTM C150. The sand and rock sources were local, Arizona aggregates used in CXT's standard concrete mix. High-range water reducers were also used for workability.

Approximately 2 yd^3 of concrete was batched at a time with approximately 3 ft^3 of that concrete being used for quality control purposes and 1.75 ft^3 used specifically for the pullout tests. Concrete used for pullout testing came from the same batches as the concrete used to pour the railroad ties.

All concrete batching was done by CXT's batch plant. Consistency and quality of this concrete was verified by the batch plant and quality control (QC) employees working for CXT.

6.2.3 Casting and Specimen Curing Procedures

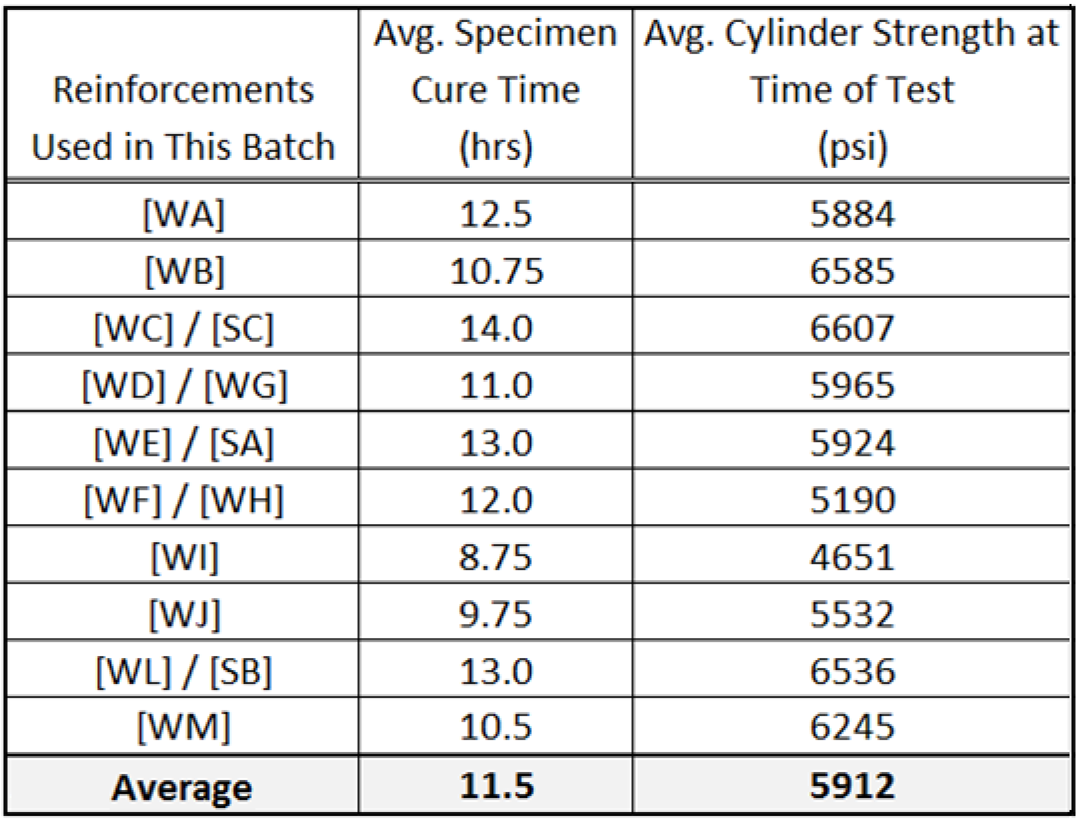
Each reinforcement was tested six times and the results averaged. All reinforcements were tested in their as-received condition during the plant phase. In addition to the pullout specimens, 12 4-in. x 8-in. cylinders were cast to test the compressive strength of the concrete. The pullout specimens and cylinders used for strength were consolidated in two lifts using a vibrating table. A slump test using a slump cone was done to measure the workability of the concrete.

The vibrating action from the vibrating table, along with the superplasticizer, provided a relatively smooth finish with no further need to smooth the surface. The specimens were covered with plastic to retain moisture during curing. They were then stored in a temperature-controlled closet at approximately 150 ^{o}F. Outside and inside of the storage closet can be seen in Figure 6.4. This allowed the specimens and cylinders used for strength to heat up similar to the concrete railroad ties. No humidity-control mechanism was present in the curing closet.

Average concrete strength at the time of pullout testing (measured from the 4-in. x 8-in. cylinders) and average specimen curing time are shown in Table 6.2 for the as-received wire and strand pullout specimens tested at CXT.

Different 4-in. x 8-in. cylinders were driven by a SureCure temperature matching system to reveal when de-tensioning could begin and to track strength throughout the duration of the cutting operation. The temperature was driven by a thermal couple embedded in the concrete ties themselves.

Table 6.2 As-received pullout batch summaries at CXT, wire, and strand



Reinforcements Used in This Batch	Avg. Specimen Cure Time (hrs)	Avg. Cylinder Strength at Time of Test (psi)
[WA]	12.5	5884
[WB]	10.75	6585
[WC] / [SC]	14.0	6607
[WD] / [WG]	11.0	5965
[WE] / [SA]	13.0	5924
[WF] / [WH]	12.0	5190
[WI]	8.75	4651
[WJ]	9.75	5532
[WL] / [SB]	13.0	6536
[WM]	10.5	6245
Average	**11.5**	**5912**

Figure 6.4 Outside and inside of temperature-controlled storage closet at CXT

6.2.4 Testing Procedures

Specimen testing began at approximately the same time as detensioning of the concrete ties. Strength of the concrete was monitored before, during, and after pullout testing took place to monitor average strength of the mortar.

A force controlled test was run in a Forney testing machine by manually controlling the flow rate of a small hydraulic pump. This pump was not servo-controlled as was the setup at KSU. The overall testing setup at CXT can be seen in Figure 6.5. The force control rate ranged from approximately 30-35 pounds/sec, which equates to 1800-2100 pounds/min. The force was applied at the bottom, and the end slip was continuously measured and recorded at the top using an LVDT. This is the same process used at KSU. The load was recorded by means of a 10,000-pound-capacity pressure transducer. Time, end slip, and force data were obtained in 0.1-second intervals. A close-up view of the specimen in the testing machine and a close-up of the LVDT mounted on the specimen can be seen in Figure 6.6.

Figure 6.5 Manually controlling force loading rate at CXT

Figure 6.6 a) Specimen in testing machine at CXT and b) LVDT on specimen at CXT

6.3 Results and Analysis

Results of the experimental, plant wire and strand testing program are presented in this section. First, results of the as-received wire pullout specimens are presented. Second, as-received strand pullout results are documented. The third section presents transfer length measurements obtained from actual pre-tensioned concrete railroad ties. Finally, analysis used for both the wire and strand bond testing is established and the findings presented.

6.3.1 Wire Pullout Results

Average as-received force vs. end slip results at CXT from each wire source are presented in Figure 6.7. The average force at each increment of end slip (0.0005 in.) was obtained by arithmetically adding the force results from each of the six individual specimens and then dividing by six. The same process was used to average the end slip measurements for each wire group.

Each line on the graph represents the average of six individual specimens from the same wire source, except for the following wires: WA and WC are represented by four specimens; WB is represented by five specimens. The reduced numbers of specimens are a result of malfunctions with the LVDT and data acquisition software. All specimens from the same wire source were cast from the same batch of concrete at the same time. Force vs. end slip graphs showing individual results of the six specimens for each wire source can be seen in Appendix N.

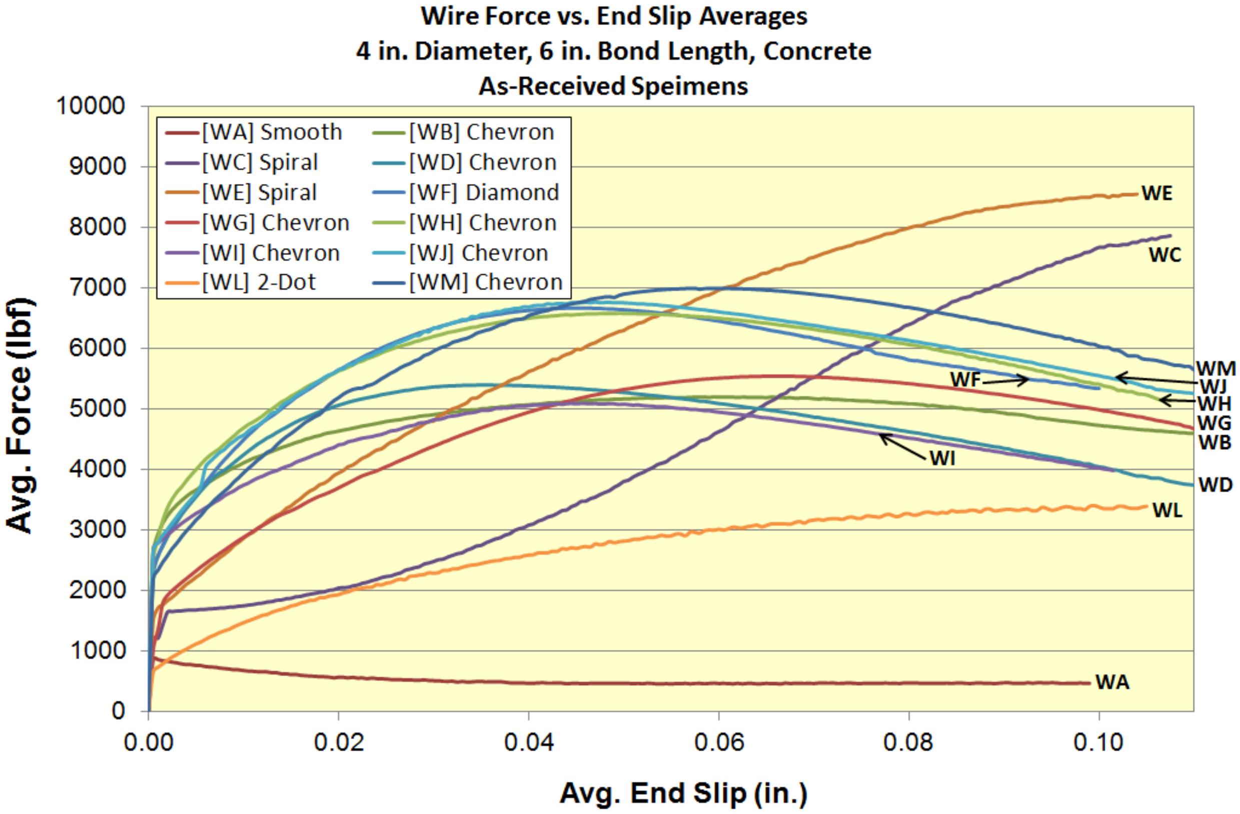


Figure 6.7 As-received wire force vs. end slip averages at CXT

6.3.2 Strand Pullout Results

Due to an error that took place in the plant, pullout specimens at CXT containing strand SB were tested using a 6-in. bond length instead of the 4-in. bond length used for strands SA and SC. Because of the different bond lengths of the specimens, the bond stress was used for the CXT results instead of pullout force. Bond stress is defined as the pullout force at any location divided by the total surface area in contact with the concrete. This surface area is mathematically defined as the perimeter of the strand multiplied by the bond length. Table 6.3 contains the bond area for strands SA, SB, and SC. All of the pullout forces from this point forward will be divided by the respective bond areas.

Average as-received bond stress vs. end slip results at CXT from each strand source are presented in Figure 6.8. The average force at each increment of end slip (0.0005 in.) was obtained by arithmetically adding the force results from each of the six individual specimens and then dividing by six. The same process was used to average the end slip measurements for each wire group.

Each line on the graph represents the average of six individual specimens from the same wire source except for WC, which is represented by four specimens. The reduced number of specimens is a result of malfunctions with the LVDT and data acquisition software. All specimens from the same strand source were cast from the same batch of concrete at the same time. Bond stress vs. end slip graphs showing individual results of the six specimens for each strand source can be seen in Appendix N.

Table 6.3 Bond areas of different bonded strand lengths

Strand Idnetification	**[SA]**	**[SB]**	**[SC]**
Indentation Type	**3/8" 7-Wire, Smooth**	**3/8" 7-wire, Indented**	**5/16" 3-wire, Smooth**
Cross-Sectional Area (in^2)	**0.0850**	**0.0850**	**0.0582**
Perimeter Length (in.)	**1.378**	**1.378**	**2.138**
6 in. Long Bond Area (in^2)	**8.268**	**8.268**	**12.828**
4 in. Long Bond Area (in^2)	**5.512**	**5.512**	**8.552**

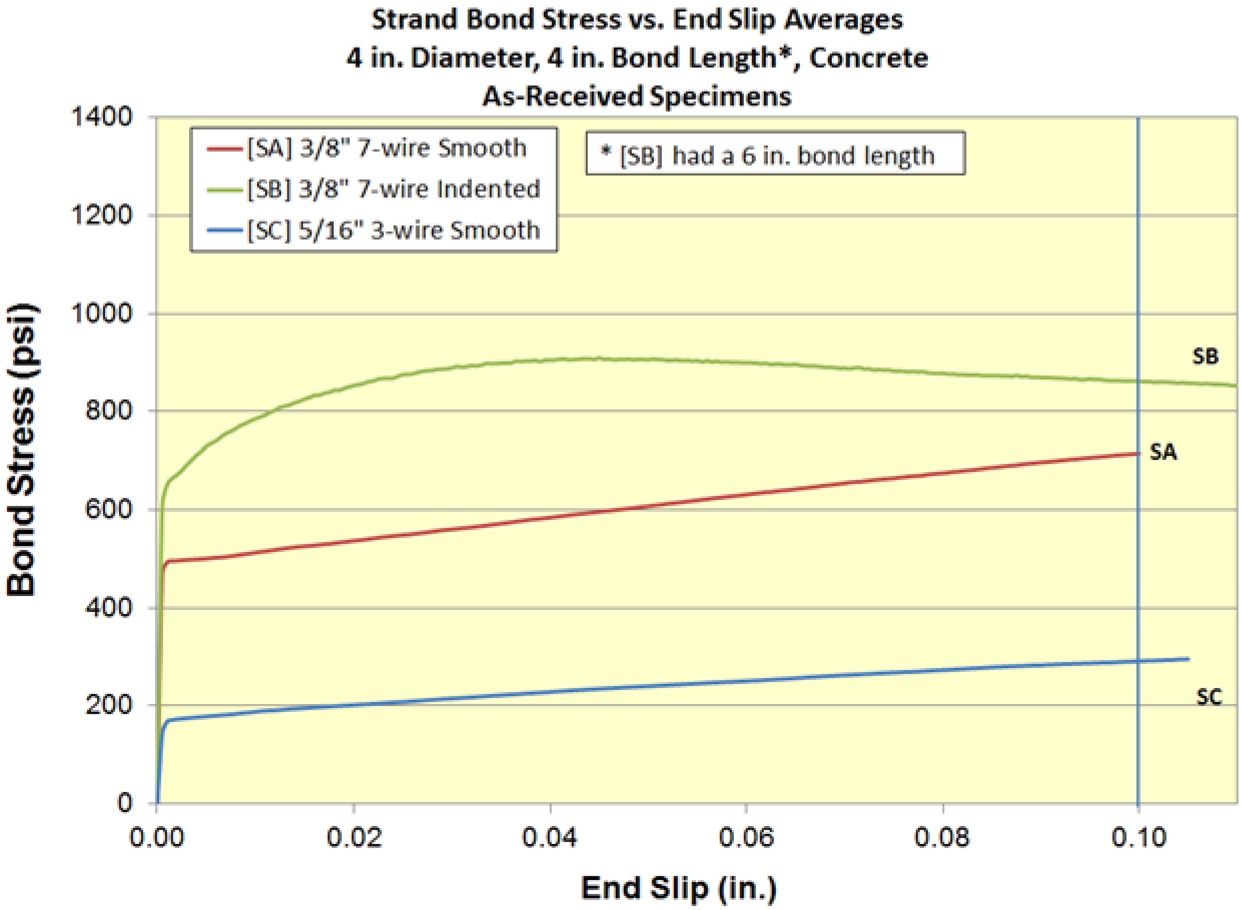


Figure 6.8 As-received strands, bond stress vs. end slip averages at CXT

6.3.3 Transfer Length Data

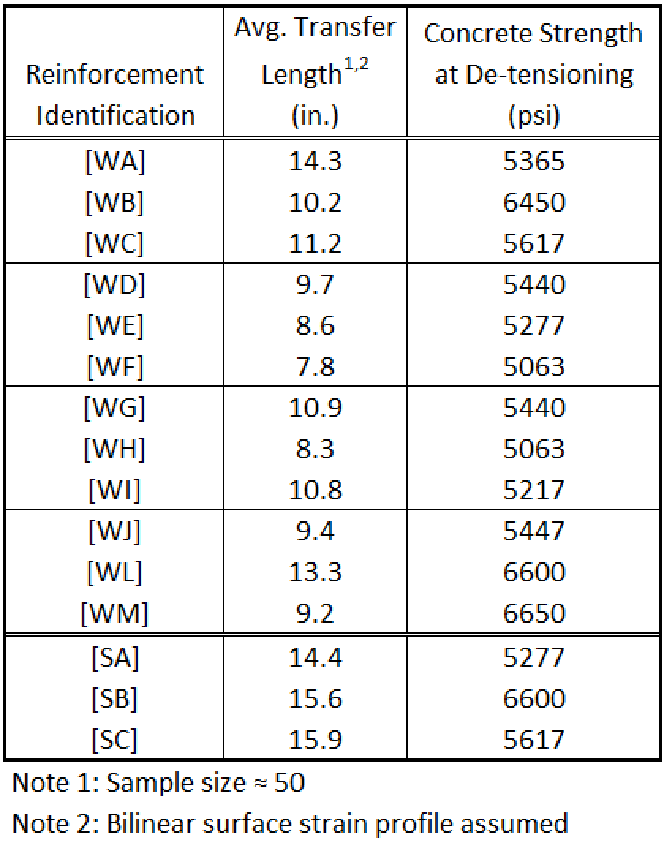
Data presented in Table 6.4 shows the average wire and strand transfer length measurements determined from the surface strain data obtained by the KSU research team while at CXT. Transfer lengths were determined from the surface strain data obtained from actual accompanying pretensioned concrete railroad ties using the same wires and strands as the pullout tests. Surface strain data was obtained for a distance of 28 inches from the tie end. A bilinear strain profile was assumed for the software that calculated the transfer lengths.

The reinforcements used for the pre-tensioned concrete railroad ties were stored and preserved along with reinforcements used for the pullout tests. Reinforcements were stored in their coils inside of a sealed shipping freight box. Inside the box were large silica-based desiccant packets to maintain surface conditions as received from the manufacturer/supplier.

Twenty-five pre-tensioned prisms were cast using each reinforcement. A transfer length was measured from each member end, resulting in a total of approximately 50 transfer lengths (50 data points). The actual number of transfer lengths obtained for each reinforcement type is shown in Table 6.1.Twenty wires were used in the concrete railroad ties containing wires. Railroad ties containing SA and SB used eight strands and ties containing SC used 12 strands. All of these steel configurations gave an almost identical total steel area due to the differences in the areas of each individual wire compared to the 3/8-in.-diameter strands (SA and SB) and the 5/16-in.-diameter strand (SC).

These concrete railroad ties were cast using the concrete mixture described in Section 6.2.2. Concrete strength at the time of de-tensioning is listed in Table 6.4. Strength was measured from a SureCure temperature-match curing system. These strengths are different than the average strength at the time of pullout testing. The testing procedure used to obtain the transfer lengths from these pre-tensioned concrete railroad ties is presented in Bodapati's 2013 paper, but is not discussed here.

Table 6.4 CXT wire and strand transfer length data



Reinforcement Identification	Avg. Transfer Length^{1,2} (in.)	Concrete Strength at De-tensioning (psi)
[WA]	14.3	5365
[WB]	10.2	6450
[WC]	11.2	5617
[WD]	9.7	5440
[WE]	8.6	5277
[WF]	7.8	5063
[WG]	10.9	5440
[WH]	8.3	5063
[WI]	10.8	5217
[WJ]	9.4	5447
[WL]	13.3	6600
[WM]	9.2	6650
[SA]	14.4	5277
[SB]	15.6	6600
[SC]	15.9	5617

Note 1: Sample size ≈ 50

Note 2: Bilinear surface strain profile assumed

6.3.4 Analysis

Analysis in this section compared results from Sections 6.3.1 (as-received wire pullout data) and 6.3.2 (as-received strand pullout data) to results from Section 6.3.3 (transfer length data). The wire analysis is given first and the strand analysis second.

6.3.4.1 Wire Pullout Analysis

Analysis of the wires was performed using the method of Section 4.3.4.5. This method uses maximum pullout force at any location less than or equal to 0.10-in. end slip and was found from the laboratory experimental program to provide the best correlation to measured transfer lengths.

The correlation was found for 1) all 12 wires and 2) for only the wires with non-continuous indentations (nine wires). This was done because the smooth and spiral wires exhibit a different slip pattern than the individually-indented wires and the researchers wanted to see whether or not a good correlation could be achieved for wires with indents specifically conforming to ASTM C881. The results of the analysis are presented in tabular form in Table 6.5. Graphical results of the analysis using all 12 wires is shown in Figure 6.9 and Figure 6.10, using only the nine-wire data set (wires with non-continuous indentations). The number of pullout tests performed for each wire source is indicated in the notes of Table 6.5. Average transfer length value is represented by approximately 50 individual transfer length measurements.

This method of analysis also provides a correlation of $R^2 = 0.680$ when all 12 wires are considered. Furthermore, this analysis gives a correlation of $R^2 = 0.825$ when considering only the wires with non-continuous indentations.

Table 6.5 As-received wires, maximum pullout force at CXT

As-Received Wire Pullout Test Results
4 in. Diameter, 6 in. Bond Length, Concrete
Maximum Pullout Force (ES ≤ 0.10 in.)

Wire	Avg. Pullout Force (lbf)	Std. Dev.[1] (lbf)	C.V.[1] (%)	Avg. Transfer Length[2] (in.)
[WA]	903	128	14.2	14.3
[WB]	5230	261	5.0	10.2
[WC]	7655	1131	14.8	11.2
[WD]	5459	596	10.9	9.7
[WE]	8526	301	3.5	8.6
[WF]	6694	701	10.5	7.8
[WG]	5554	386	6.9	10.9
[WH]	6618	1017	15.4	8.3
[WI]	5175	203	3.9	10.8
[WJ]	6789	343	5.1	9.4
[WL]	3438	325	9.4	13.3
[WM]	7004	726	10.4	9.2

Note 1 : Sample Size = 6, WA = 4, WB = 5, WC = 4
Note 2 : Sample Size ≈ 50, Bilinear surface strain profile assumed

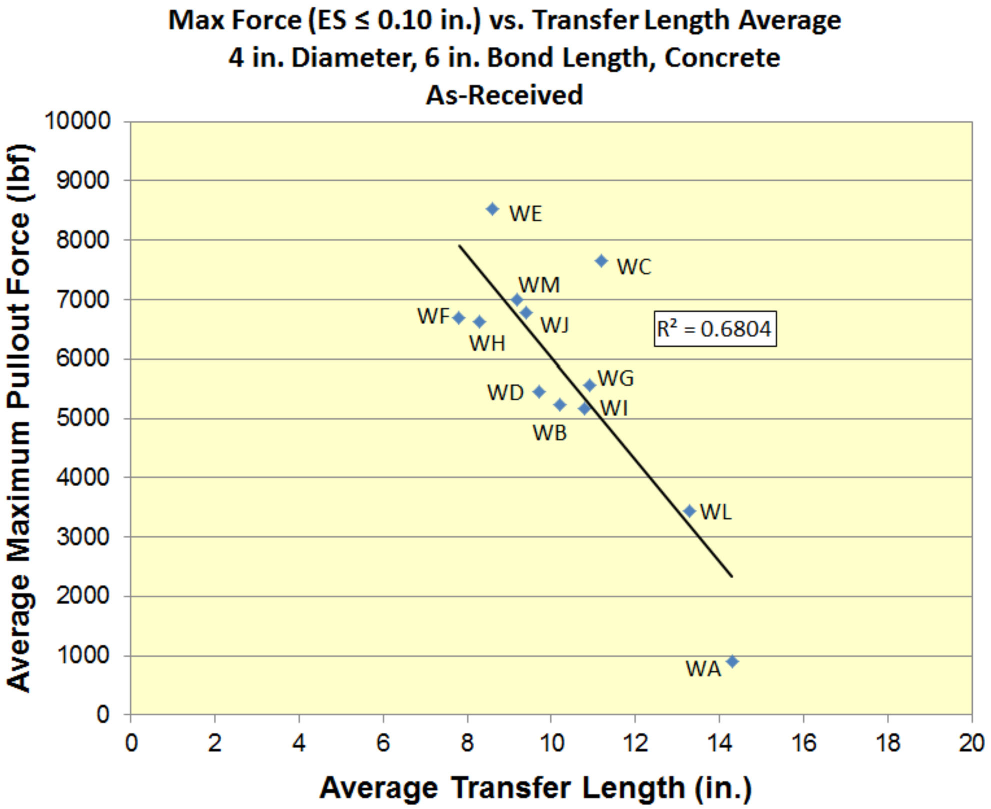


Figure 6.9 As-received wires, maximum pullout force at CXT

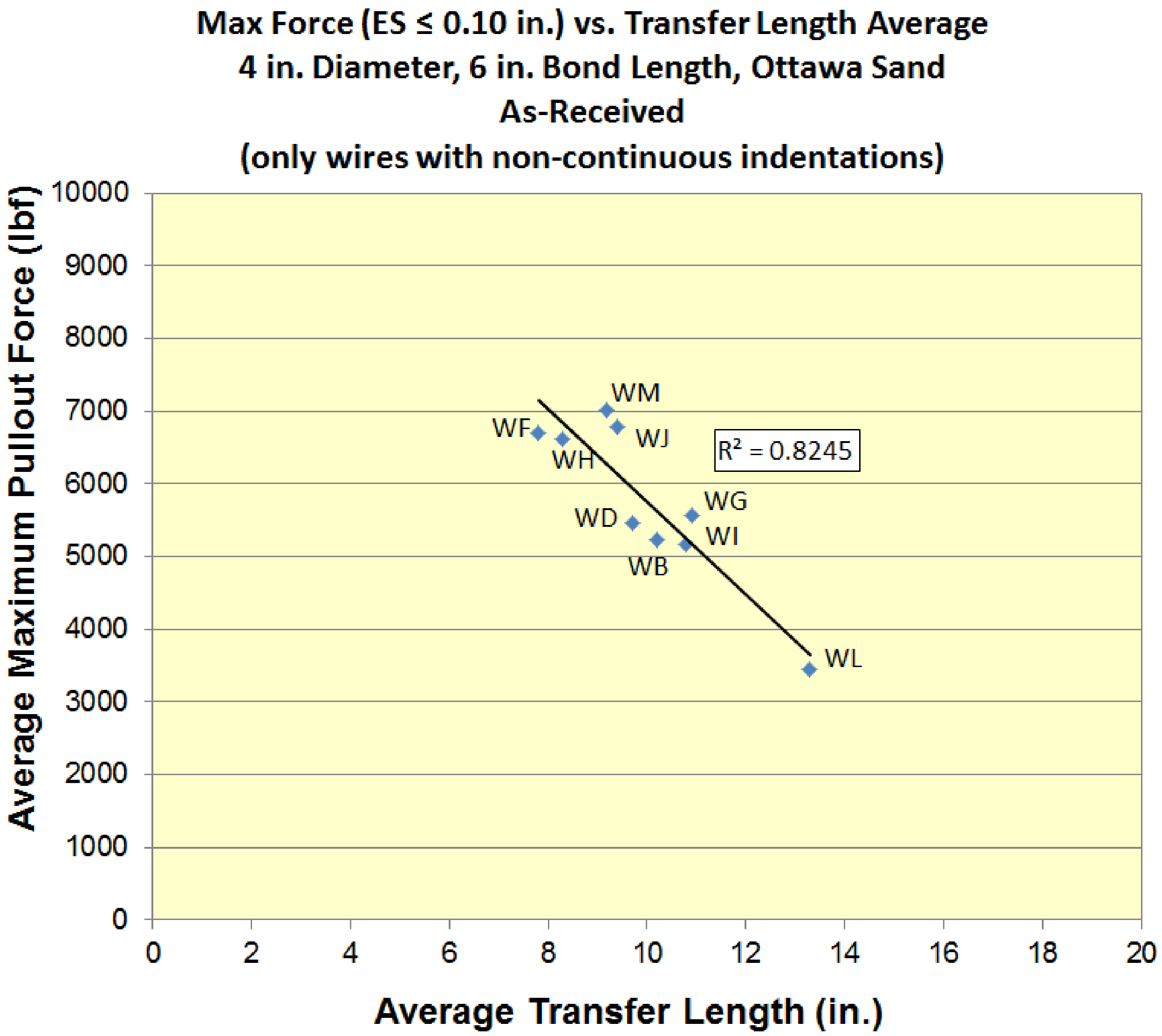


Figure 6.10 As-received wires, maximum pullout force at CXT (individual-indents only)

This analysis shows that even when using concrete, the wire pullout test described in Appendix I is a good indicator of transfer length for wires with non-continuous indentations. Additionally, this analysis shows the wire pullout test to be a fair indicator of transfer lengths for all wire indent types.

This is an interesting conclusion given the wide variation of concrete strengths (shown in Table 6.4) during each set of pullout tests for each wire. It is important to clarify the variable concrete strength during the pullout tests does not allow us to compare relative bond performance between the wire groups. However, since the pullout tests were performed at roughly the same time as the de-tensioning of the concrete railroad ties, these pullout concrete strengths are similar to the actual strength of the concrete used in the railroad ties. By performing the pullout tests at roughly the same time as de-tensioning occurred, the variable of concrete strength was more or less negated as shown by the good correlation between maximum pullout force and measured transfer length. This makes sense because the maximum pullout force is assumed to increase and the transfer length assumed to decrease when the concrete strength increases.

It is hypothesized the wire pullout tests would have had even better correlation with the transfer lengths measured from the concrete railroad ties had the pullout specimens been cured at the same temperature as the ties themselves. This could have been achieved by driving the temperature of the pullout specimens using a temperature-match curing system.

6.3.4.2 Strand Pullout Analysis

Analysis of the strands was performed according to the method laid out in the NASP (Russell, 2006) and NCHRP 603 (Ramirez and Russell, 2008) reports. This standard test for strand bond uses the pullout force at 0.10 in. of free-end slip. The analysis here correlates the measured transfer lengths to the bond stress corresponding to this pullout force. Results of the analysis using the three strand sources are given in Table 6.6 and Figure 6.11. The number of pullout tests performed for each strand source is indicated in the notes of Table 6.6. The average transfer length value is represented by approximately 50 individual transfer length measurements.

This analysis gives a correlation of $R^2 = 0.200$ between the bond stress recorded at 0.10 in. of end slip and the measured transfer length. This analysis shows when using concrete and only three strand sources, the strand pullout test described in Section 6.2 is a poor indicator of transfer length for smaller diameter strands.

Table 6.6 As-received strands, bond stress at 0.10 in. end slip at CXT

As-Received Strand Pullout Test Results 4 in. Diameter, 4 in. Bond Length[2], Concrete Pullout Force at 0.10 in. End Slip				
Strand	Avg. Bond Stress[1] (psi)	Std. Dev. (psi)	C.V. (%)	Avg. Transfer Length[3] (in.)
[SA]	715	100	14.0	14.4
[SB]	862	31	3.6	15.6
[SC]	291	85	29.0	15.9

Note 1: Sample Size = 6, SC = 4

Note 2: Strand [SB] has a 6 in. bond length

Note 3: Sample Size ≈ 50, Bilinear surface strain profile assumed

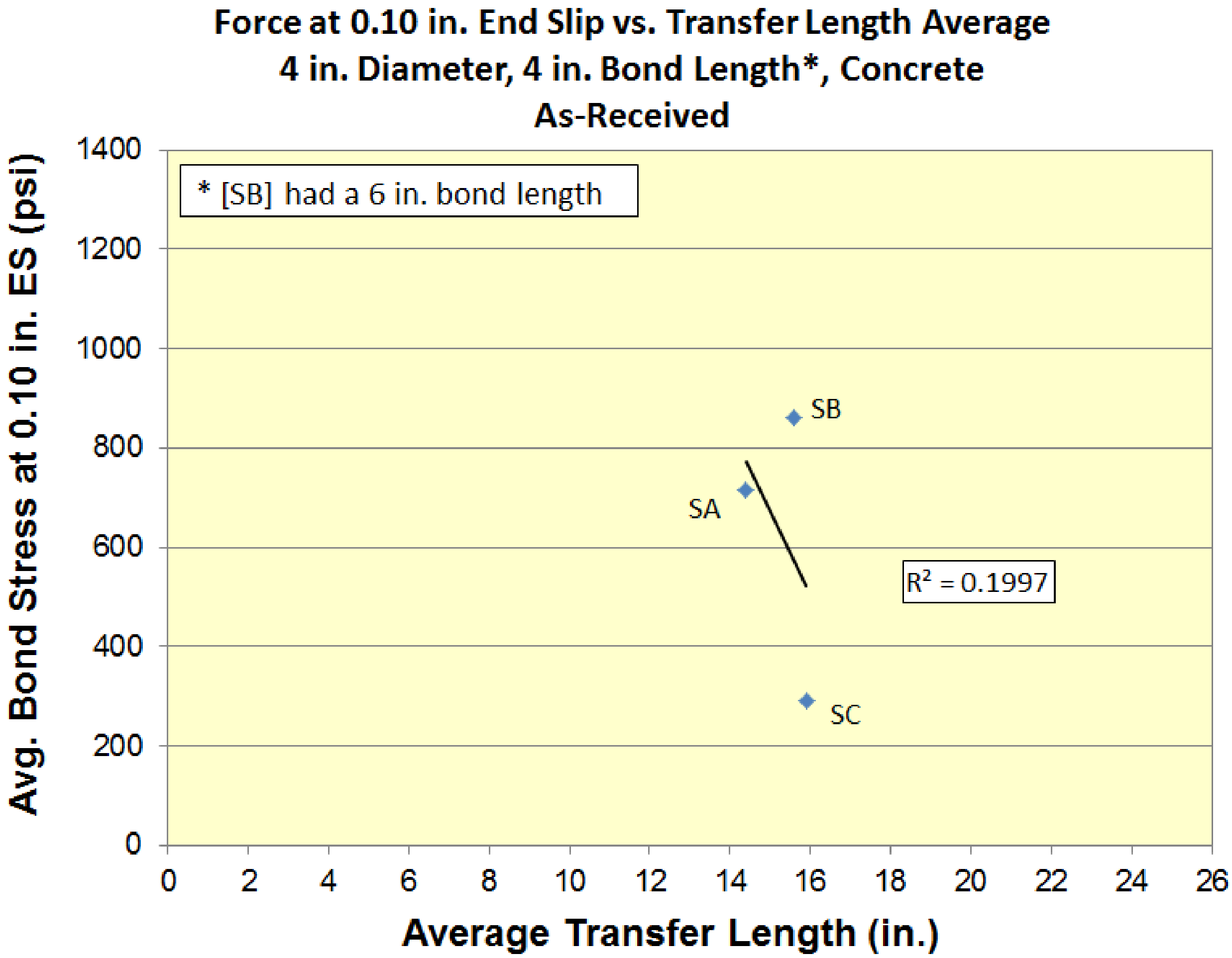


Figure 6.11 As-received strands, bond stress at 0.10 in. end slip at CXT

Chapter 7 - Comparing Results of Lab and Plant Phases

Chapter 7 compares as-received results of the wire and strand bond pullout tests between the lab and the plant phases. The lab tests are un-tensioned and were performed in mortar, whereas the plant tests are un-tensioned and were performed in concrete.

Any test results obtained in the laboratory will commonly be referred to as Kansas State University (KSU) tests, and any tests were performed at the concrete railroad tie plant will commonly be referred to as CXT Concrete Ties (CXT) tests.

7.1 Comparison of Wire Data

7.1.1 Procedural Differences between Lab and Plant, Wire

There are a number of procedural similarities and differences between the wire pullout tests performed in the lab at Kansas State University (KSU) and the wire pullout tests performed in the plant at CXT Concrete Ties (CXT).

There are three main similarities between the lab and plant phases. First, both tests were un-tensioned. Second, force was applied at the bottom of the specimen and an LVDT was placed on the top of the specimen to measure the free-end slip in both testing locations. Third, the specimen sizes at both locations were almost identical. Both wire specimens utilized a 4-in.-diameter steel tube with a total length of 8-in. A 6-in. by 6-in. steel plate was attached at the bottom. Within the 8-in.-long steel tube, there was a 6-in. embedment (bond) length with a 2-in. long duct tape bond breaker. The wire extended past the top surface approximately two inches and below the plate approximately 10 inches to be used to apply force. The schematic of the specimens used at KSU can be seen in Figure 4.14 and the schematic of the specimens used at CXT can be seen in Figure 6.1. Again, they have some minor differences but are theoretically identical.

The main difference between the lab and plant phases is that mortar was used during the lab pullout tests at KSU and concrete was used during the plant pullout tests at CXT. This was a planned research variable. Another difference – albeit an unplanned, but unavoidable one – was the strength at which each pullout test was performed. Pullout tests performed at KSU were tested with mortar batches consistently around 4500 psi. Pullout tests performed at CXT were tested with concrete batches that fluctuated in strength. This variation in strength occurred because the pullout tests at CXT were performed at approximately the same time as the railroad ties were de-tensioned (to be used to take transfer length measurements). Average mortar and concrete strengths for each set of wire pullout tests can be seen in Table 7.1. Additionally, the force-controlled loading rate was held perfectly constant (steady) at a rate of 2000 pounds/min. during testing at KSU, whereas the force-controlled loading rate ranged from approximately 1800-2100 pounds/min. at CXT. The KSU tests were able to remain at a constant loading rate due to the servo-hydraulic actuator and computer software, which precisely controlled the hydraulic fluid levels. The CXT tests were run in a Forney testing machine in which the small hydraulic pump could only be manually controlled using a screw-type valve. The last major difference between the two testing sites is the curing methodology. The pullout specimens and mortar cubes used to test the compressive strength at KSU were stored for curing in a temperature- and moisture-controlled room. Details of this curing methodology can be found in Section 4.2.4. The pullout specimens and 4-in. x 8-in. cylinders used to test the compressive strength at CXT were stored in a temperature-controlled closet, but were not humidity controlled. Details of this curing methodology can be found in Section 6.2.3.

7.1.2 As-Received Wire Results

This section presents results of the as-received wire pullout specimens performed at KSU and at CXT. Twelve of the 13 wires used in this study were tested both at KSU and at CXT. WK was not tested at CXT due to timing constraints.

Average pullout force vs. end slip graph for each wire source is shown in Figure 7.1 through Figure 7.12. Each “KSU average” and “CXT average” line on the graphs represents the average of six individual specimens from the same wire source, except for the following wires: the WA and WC data sets at CXT are represented by four specimens; the WB data set at CXT is represented by five specimens. The reduced numbers of specimens are a result of malfunctions with the LVDT and data acquisition software while at CXT. Results of the individual pullout tests comparing six KSU specimens to six CXT specimens for each wire source can be seen in Appendix O.

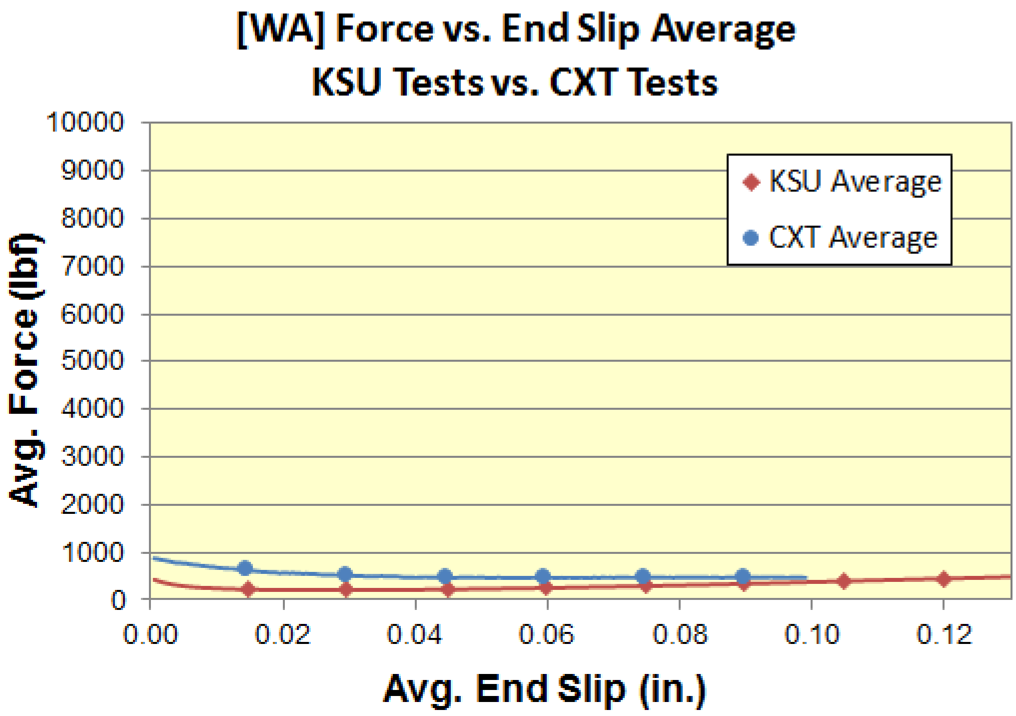


Figure 7.1 [WA] force vs. end slip average graphs, KSU vs. CXT

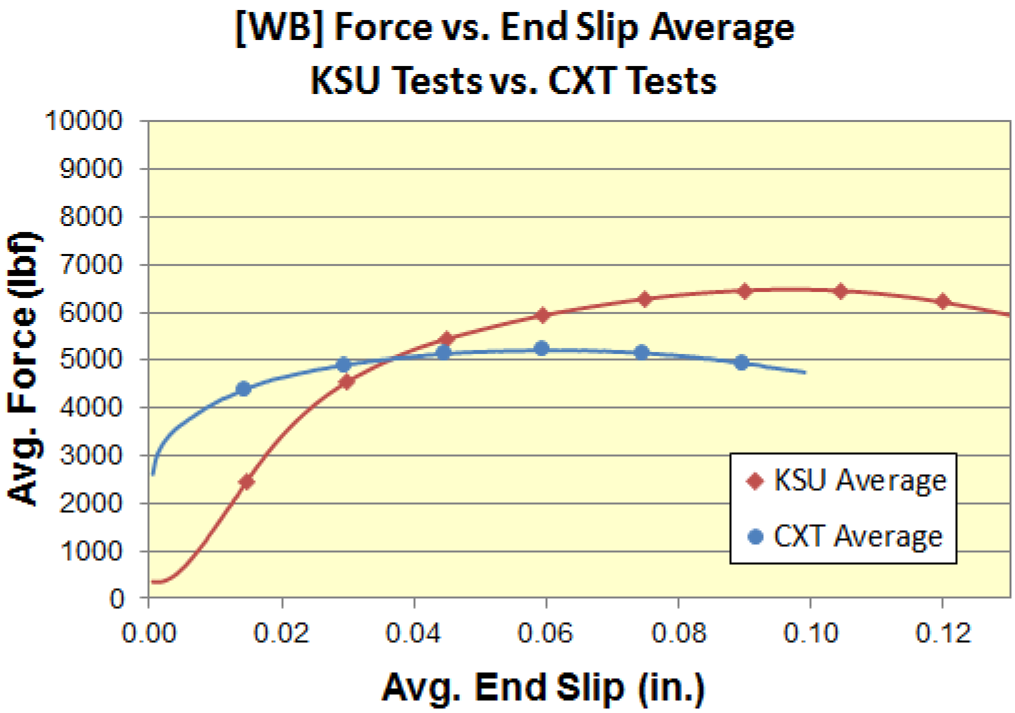


Figure 7.2 [WB] force vs. end slip average graphs, KSU vs. CXT

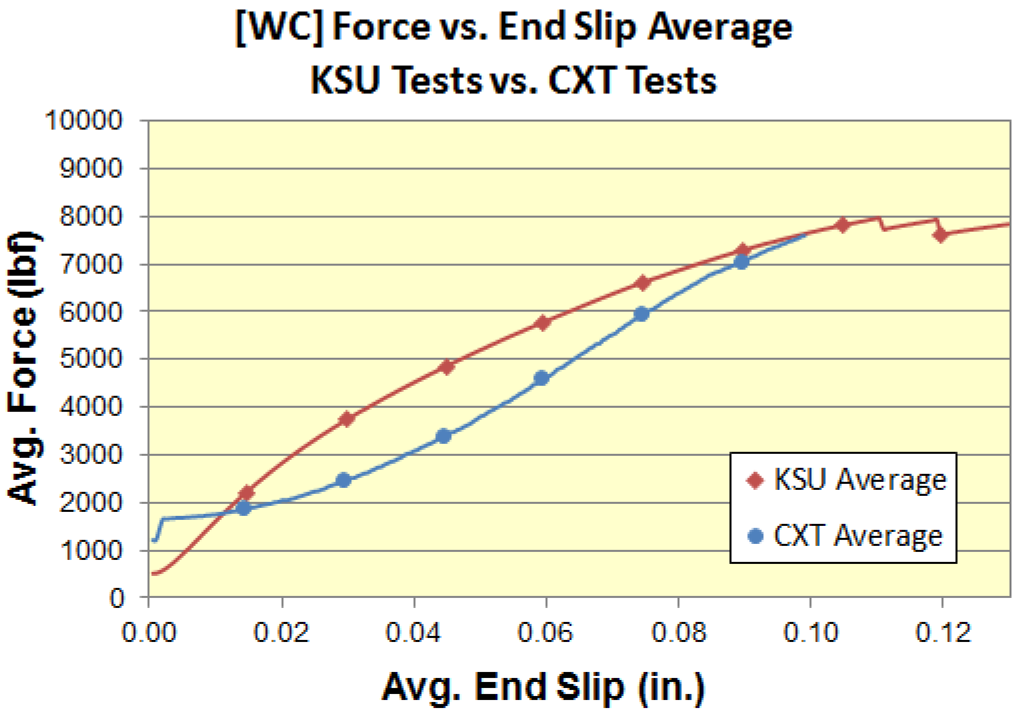


Figure 7.3 [WC] force vs. end slip average graphs, KSU vs. CXT

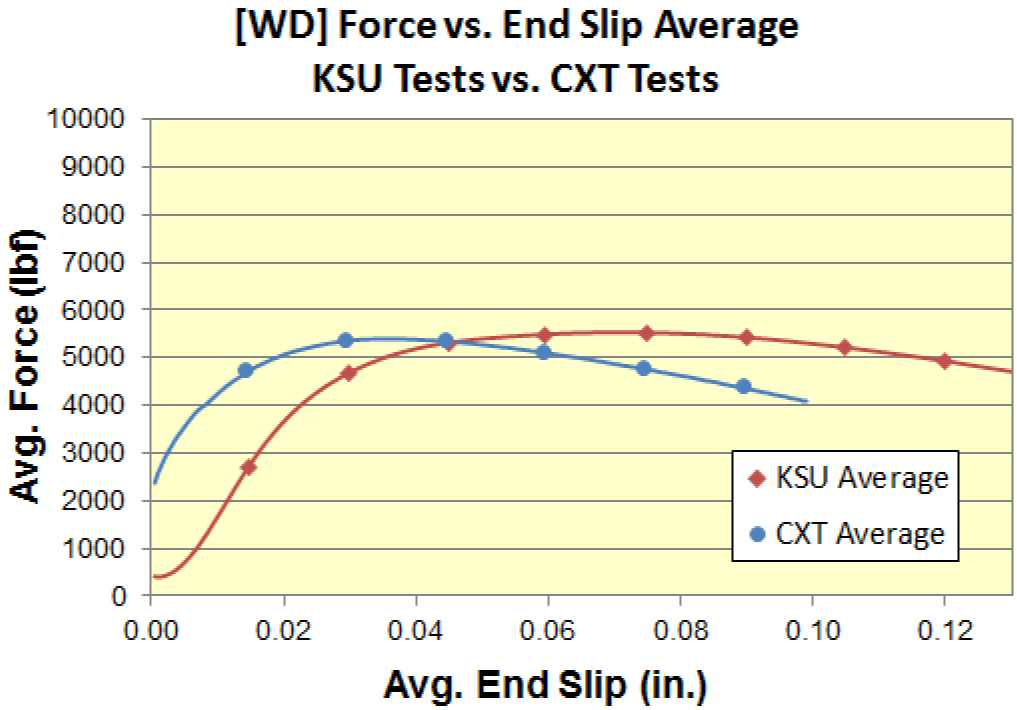


Figure 7.4 [WD] force vs. end slip average graphs, KSU vs. CXT

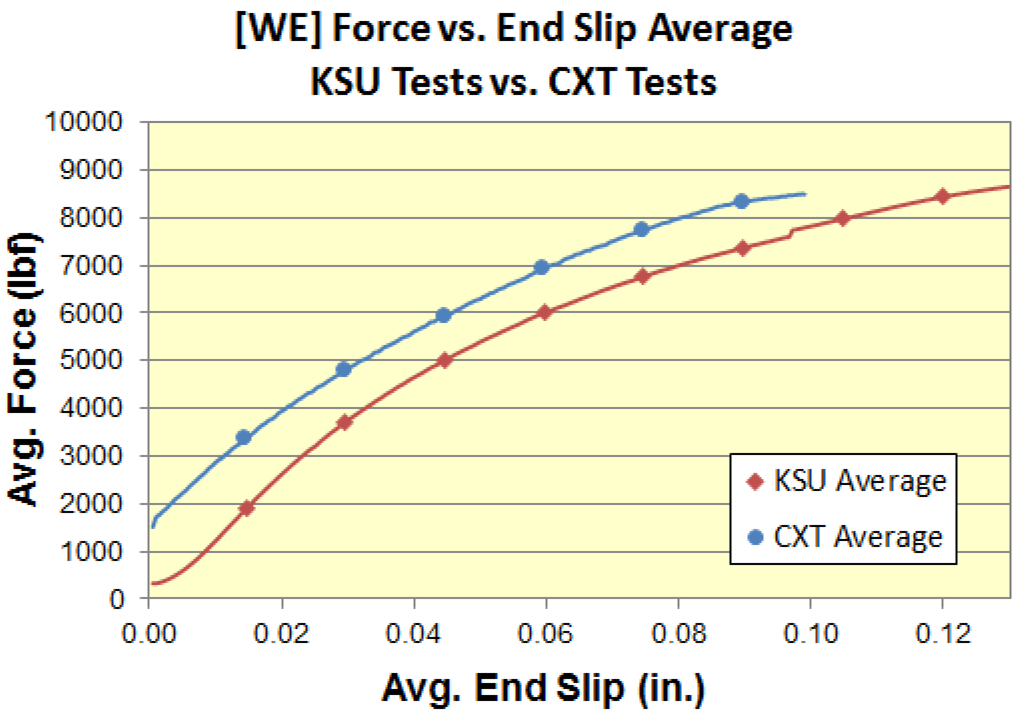


Figure 7.5 [WE] force vs. end slip average graphs, KSU vs. CXT

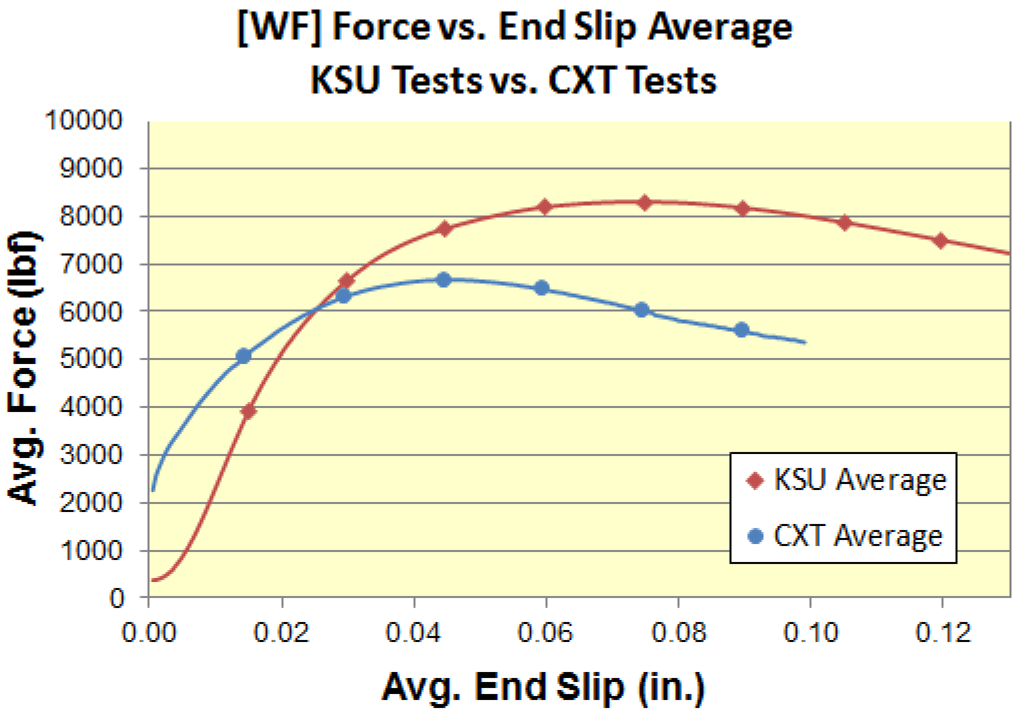


Figure 7.6 [WF] force vs. end slip average graphs, KSU vs. CXT

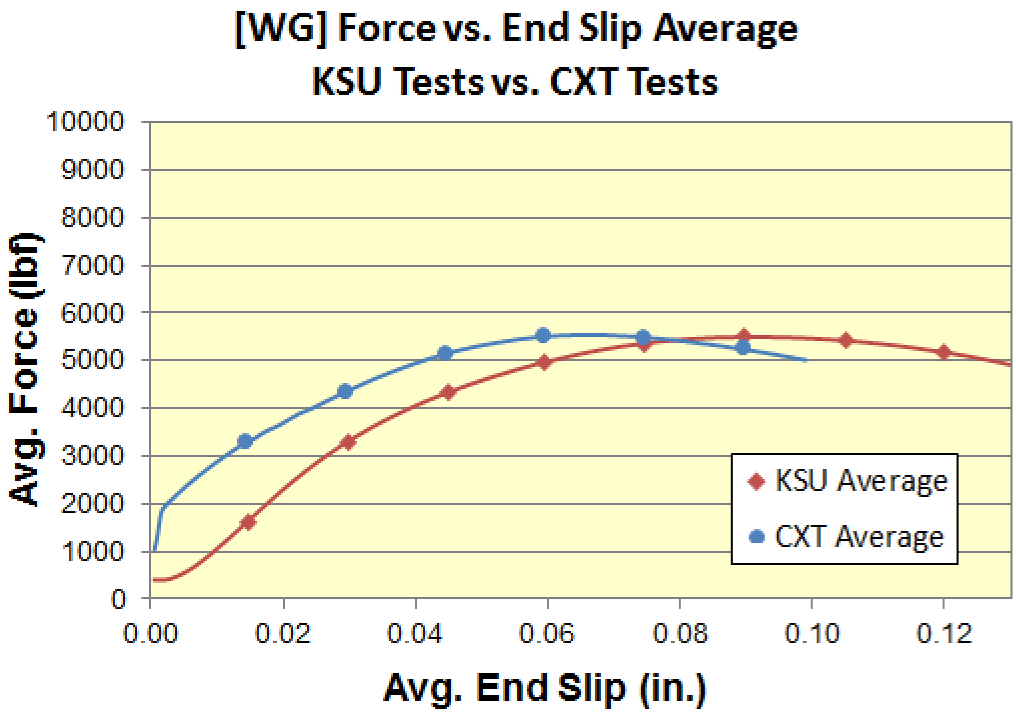


Figure 7.7 [WG] force vs. end slip average graphs, KSU vs. CXT

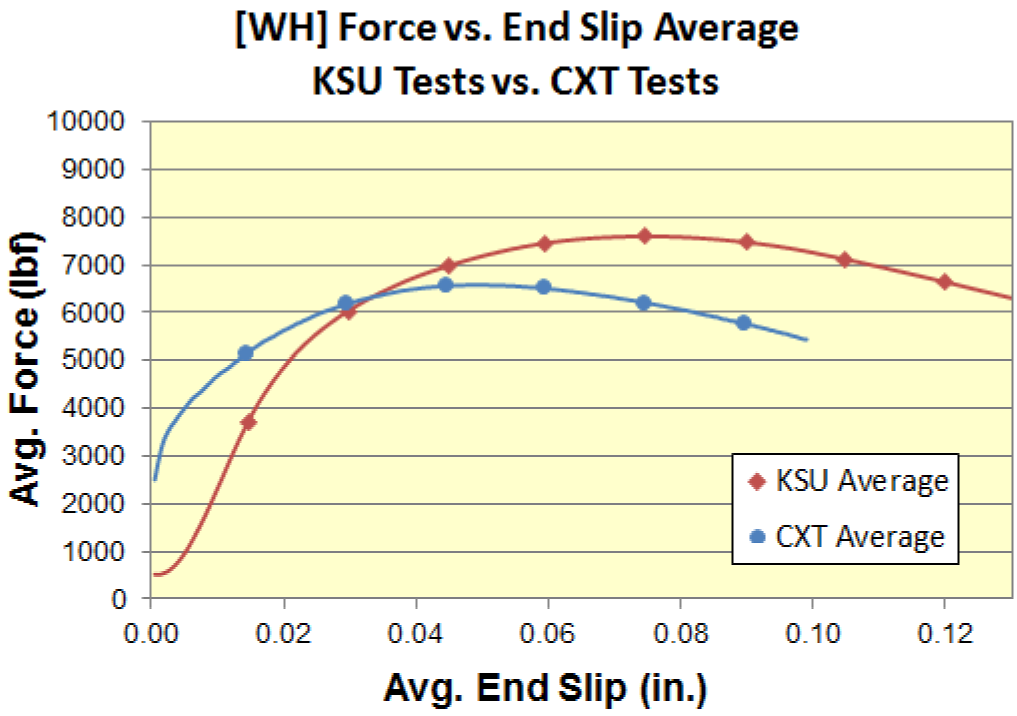


Figure 7.8 [WH] force vs. end slip average graphs, KSU vs. CXT

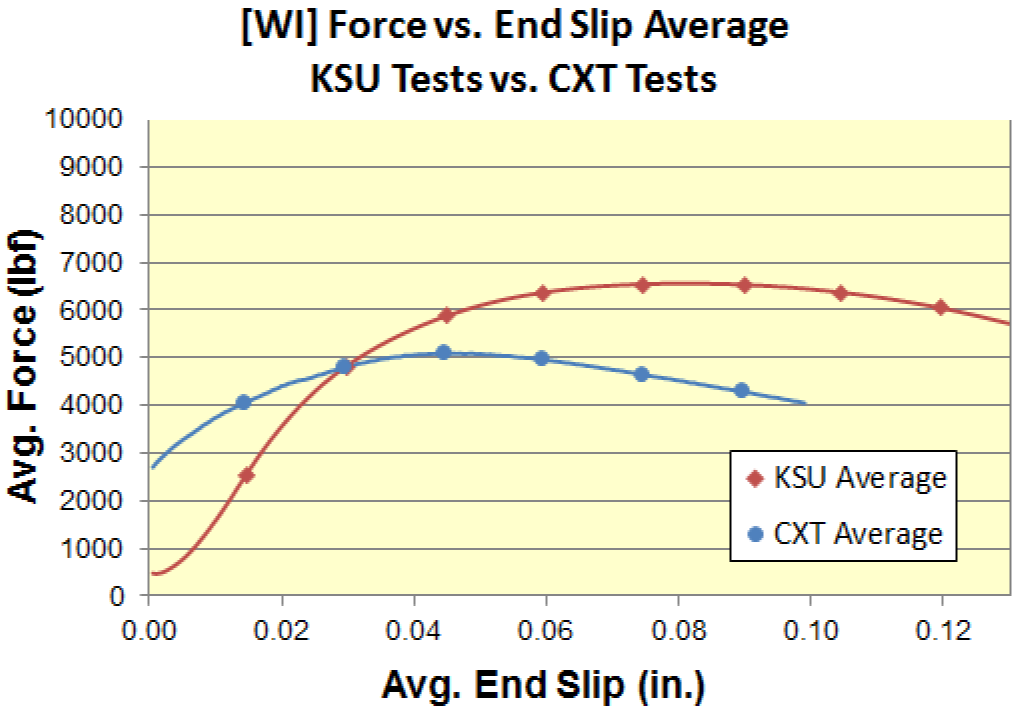


Figure 7.9 [WI] force vs. end slip average graphs, KSU vs. CXT

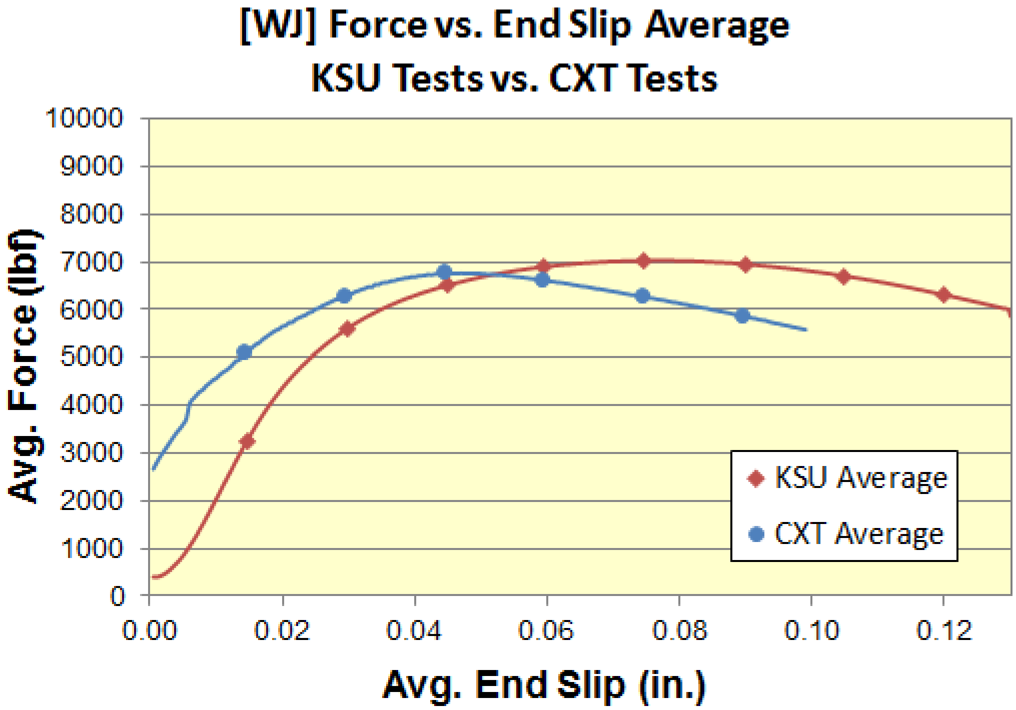


Figure 7.10 [WJ] force vs. end slip average graphs, KSU vs. CXT

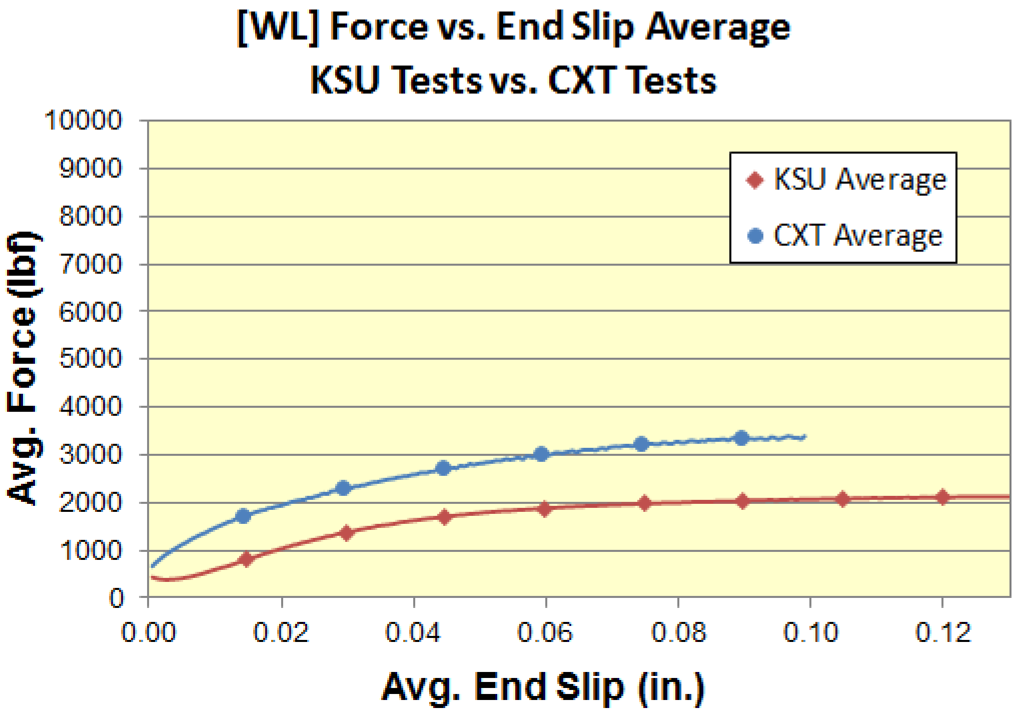


Figure 7.11 [WL] force vs. end slip average graphs, KSU vs. CXT

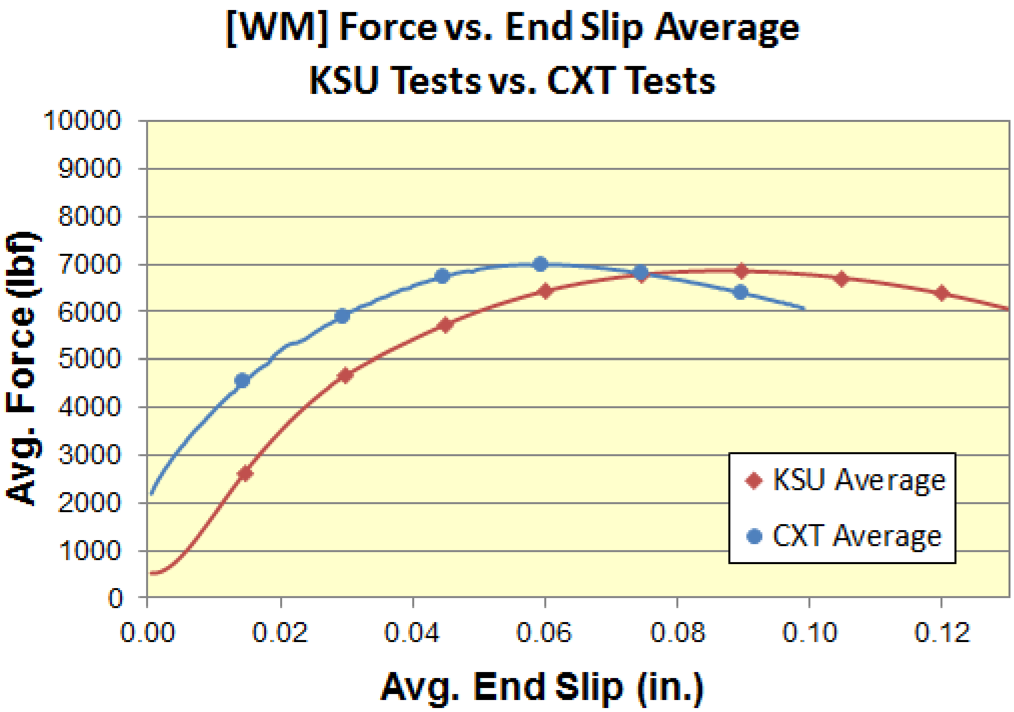


Figure 7.12 [WM] force vs. end slip average graphs, KSU vs. CXT

7.1.3 Analysis of KSU Pullout Tests vs. CXT Pullout Tests

All methods of analysis in this section compare results from Section 4.3.1 (as-received wire pullout data at KSU) to results from Section 6.3.1 (as-received wire pullout data obtained at CXT). As per Section 4.3.4.5 of this report, wire data obtained at the max pullout force occurring at a location equal to or less than 0.10 in. of end slip was used to compare the KSU and CXT data sets. This was done for all 12 wires and for only the wires with non-continuous indentations (nine wires).

Results of this analysis are presented in Table 7.1 and include the average maximum pullout forces, standard deviations, coefficient of variations (C.V.), and average mortar/concrete strengths at the time of testing for both KSU and CXT data sets. The data are also represented graphically for the data sets including all 12 wires and for the data set including only wires with non-continuous indentations in Figure 7.13 and Figure 7.14, respectively. Each value in the table and each point on the graph represents the average of the individual pullout forces measured at end slips less than or equal to 0.10 in. of end slip. The x-axis (abscissa) shows these forces taken from CXT pullout tests. The y-axis (ordinate) shows these forces obtained from KSU pullout tests. The R^2 is the correlation between these two averaged data sets.

The “Perfect Test” line represents the data of a fictional test in which the maximum pullout force at KSU was identical to the maximum pullout force at CXT for all pullout tests. “The nearness of the data to the ‘perfect line’ is an indicator of whether the test is repeatable and reproducible between test sites” (Russell and Paulsgrove, 1999b). The tests performed at KSU and CXT are fundamentally different (one being in mortar, the other in concrete), but the “Perfect Test” line still gives some insight into the similarities and differences between the two tests.

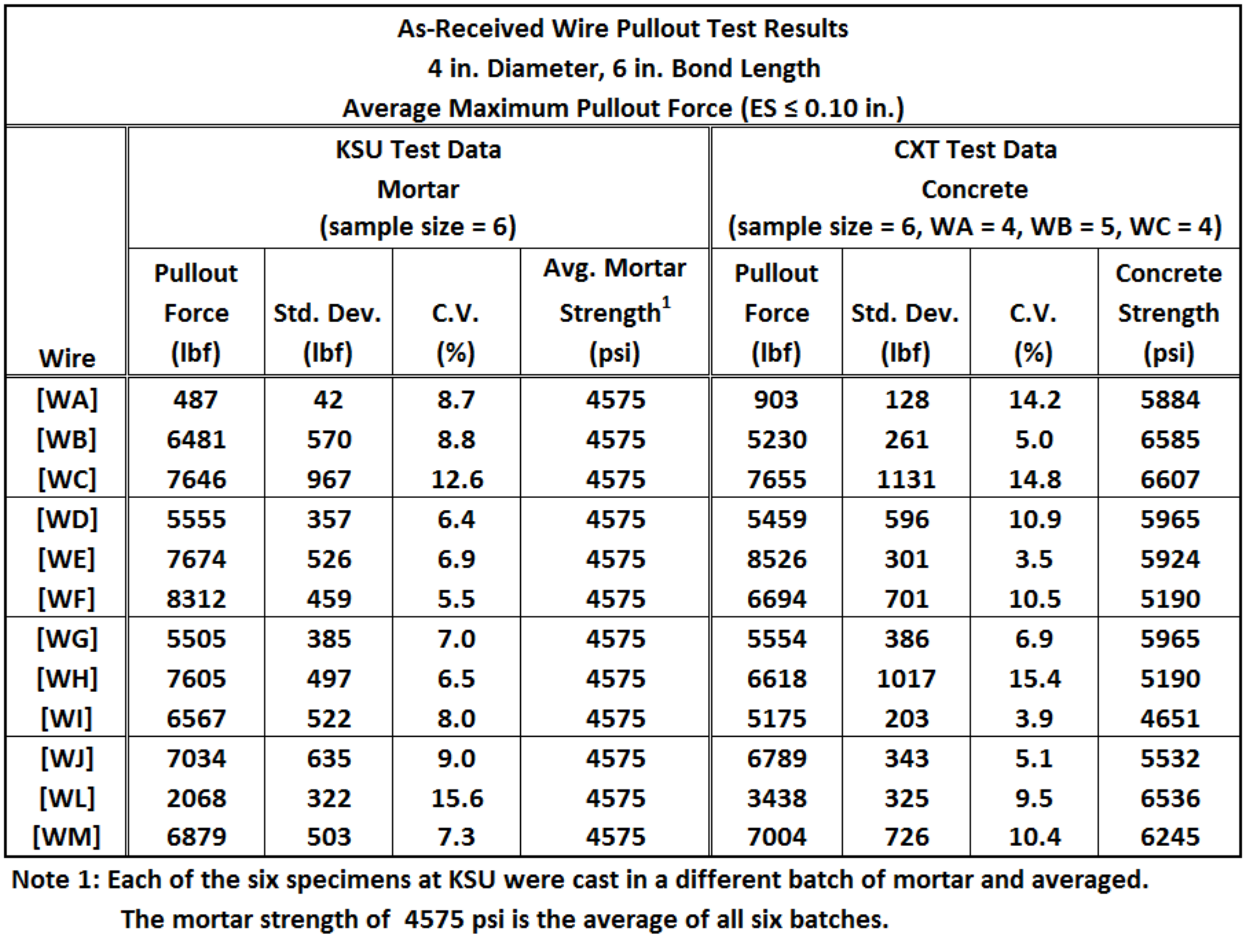
From Table 7.1 it can be seen that results from KSU and max pullout force results from CXT are relatively similar. Pullout forces from both sites showed similar scatter. The average coefficients of variation (C.V.) were 8.5% and 9.2% for values obtained at KSU and CXT, respectively. Neither of the testing sites showed a propensity to produce higher or lower results than the other. Four of the 12 wire groups (WB, WF, WH, and WI) tested at KSU gave noticeably higher results than the corresponding wire groups at CXT. Similarly, three of the 12 wire groups (WA, WE, and WL) tested at CXT gave noticeably higher results than the corresponding wire groups at KSU. The remaining five wire groups (WC, WD, WG, WJ, and

WM) had nearly identical maximum pullout forces at both testing locations. As can be seen in Figure 7.1 through Figure 7.12, the maximum force for the tests performed at KSU generally occurred at a higher end slip value than the maximum forces for the tests performed at CXT. For example, Figure 7.7 shows that despite the maximum force *value* being nearly identical for wire WG, *location of this value* occurs at approximately 0.09 in. of end slip at KSU and at approximately 0.06 in. of end slip at CXT.

When all 12 wires are included in the data sets, a correlation of $R^2 = 0.861$ was achieved. With the data sets containing only the chevron-indented wires (nine wires), a correlation of $R^2 = 0.782$ was achieved. Both of these values show very good correlation for the two different testing methodologies, especially since the tests at KSU were performed in mortar and the tests at CXT were performed in concrete (and the concrete had relatively variable strengths). Additionally, orientations of the actual test results to the “Perfect Test” lines indicate the two tests are relatively similar, repeatable, and reproducible.

Another point of interest is the point of first slip. This can be seen in Figure 7.1 through Figure 7.12 as the force at which end slip begins to occur. Since the LVDT is taking readings at the opposite end from the applied force, it does not record any readings until the cohesion and/or mechanical interlock along the entire length of the wire is broken. In mortar, the point of first slip is assumed to occur after cohesion alone is overcome. For concrete, the point of first slip is assumed to occur after both cohesion and mechanical interlock between the steel and aggregates is overcome. For tests performed at KSU, the point of first slip in the mortar mixture occurred between 331 and 522 pounds, approximately the same force. For the tests performed at CXT, the point of first slip in the concrete mixture was much more variable. These forces ranged from 665 to 2701 pounds.

Table 7.1 As-received wires, maximum pullout force data, KSU vs. CXT



As-Received Wire Pullout Test Results
4 in. Diameter, 6 in. Bond Length
Average Maximum Pullout Force (ES ≤ 0.10 in.)

Wire	KSU Test Data Mortar (sample size = 6)				CXT Test Data Concrete (sample size = 6, WA = 4, WB = 5, WC = 4)			
	Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Avg. Mortar Strength[1] (psi)	Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Concrete Strength (psi)
[WA]	487	42	8.7	4575	903	128	14.2	5884
[WB]	6481	570	8.8	4575	5230	261	5.0	6585
[WC]	7646	967	12.6	4575	7655	1131	14.8	6607
[WD]	5555	357	6.4	4575	5459	596	10.9	5965
[WE]	7674	526	6.9	4575	8526	301	3.5	5924
[WF]	8312	459	5.5	4575	6694	701	10.5	5190
[WG]	5505	385	7.0	4575	5554	386	6.9	5965
[WH]	7605	497	6.5	4575	6618	1017	15.4	5190
[WI]	6567	522	8.0	4575	5175	203	3.9	4651
[WJ]	7034	635	9.0	4575	6789	343	5.1	5532
[WL]	2068	322	15.6	4575	3438	325	9.5	6536
[WM]	6879	503	7.3	4575	7004	726	10.4	6245

Note 1: Each of the six specimens at KSU were cast in a different batch of mortar and averaged.
The mortar strength of 4575 psi is the average of all six batches.

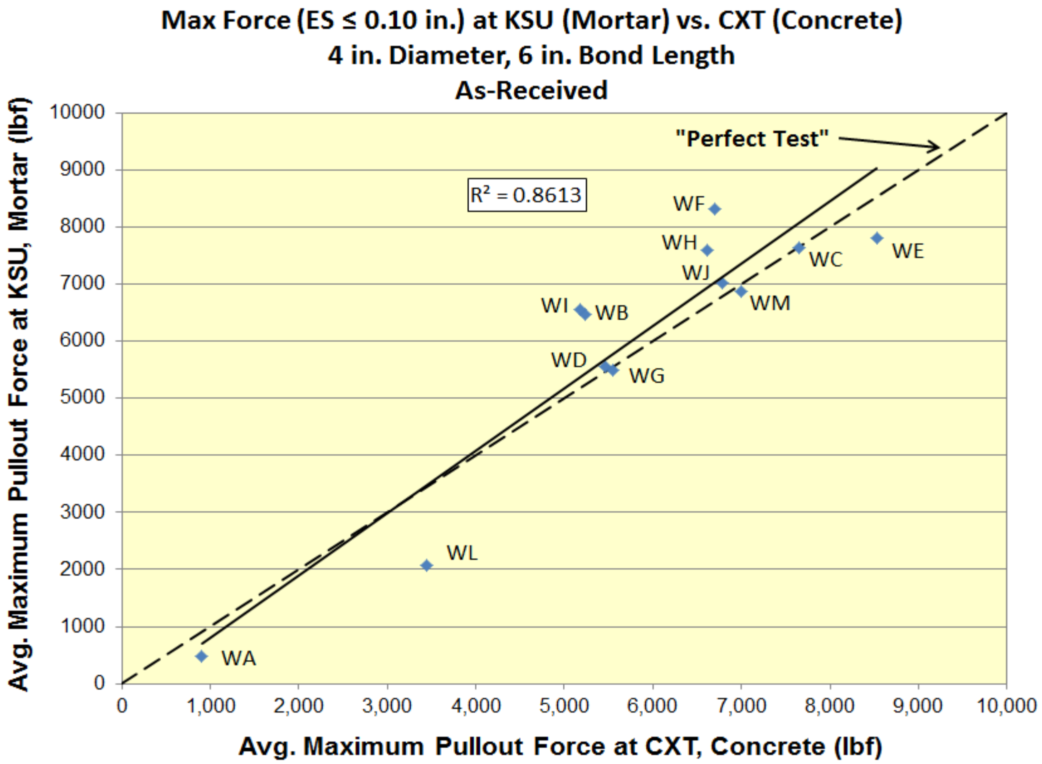


Figure 7.13 As-received wires, maximum pullout force data, KSU vs. CXT

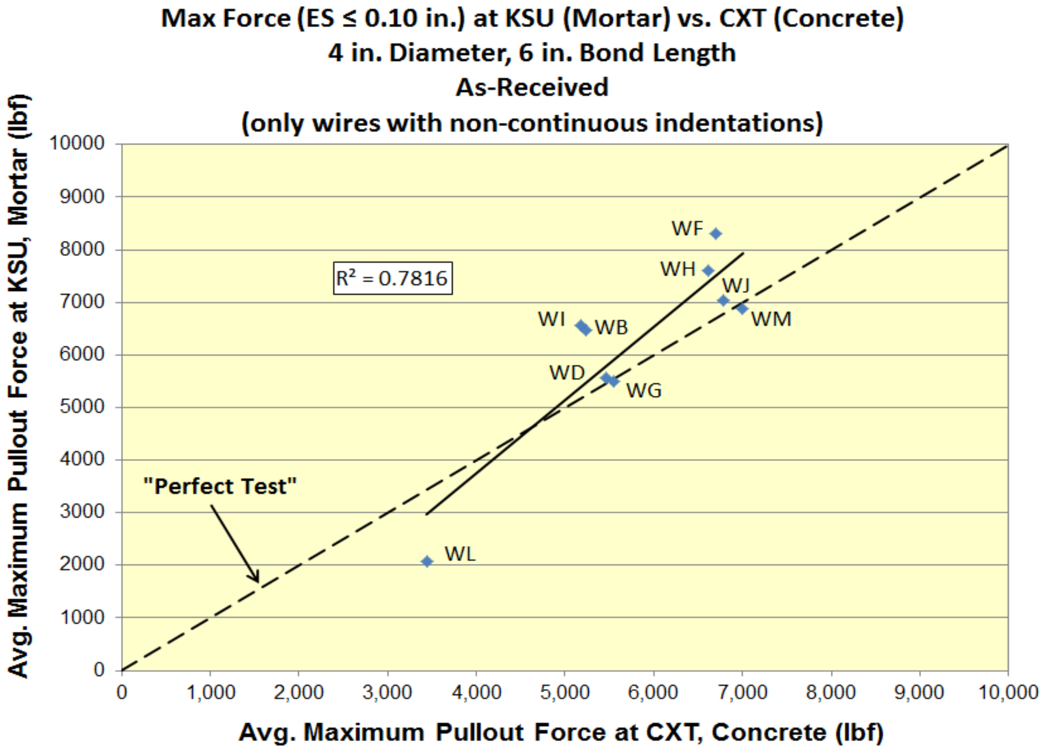


Figure 7.14 As-received wires, maximum pullout force data, KSU vs. CXT (individual-indents only)

7.1.4 Analysis of KSU Pullout Tests vs. CXT Transfer Length Measurements

The analysis presented in this section compares results from Section 4.3.1 (as-received wire pullout data at KSU) to results from Section 6.3.3 (as-received transfer length measurements obtained at CXT).

This analysis is the capstone of the wire bond testing program as a quality control test. It focuses on the question regarding bond testing the railroad industry is interested in: “Can a quality control wire pullout test performed in a lab be used to predict the actual measured transfer lengths produced at a plant?” The desire is to be able to test small samples of the wire in a relatively cheap quality control test and to be able to use those test results to predict the bond quality (and transfer length) of actual concrete railroad ties with relative certainty. This section aims to answer that question exactly.

A coefficient of determination (R^2) value was calculated by comparing the pullout force measured at KSU to the transfer lengths measured at CXT. As per Section 4.3.4.5 of this report, the pullout test data obtained at the max pullout force occurring at a location equal to or less than 0.10 in. of end slip was used. These pullout forces were obtained from un-tensioned pullout tests in mortar performed at Kansas State University. Pullout tests follow the testing methodology and protocol set forth in Appendix I. Transfer lengths were obtained from actual pretensioned concrete railroad ties cast at CXT Concrete Ties in Tucson, Ariz.

The correlation was found for 1) all 12 wires and 2) for only the chevron-indented wires, as has been the case for the majority of the wire testing. Results of the average maximum force compared with the average transfer lengths can be seen in Table 7.2. Figure 7.15 shows results of the data set containing all 12 wires and Figure 7.16 shows the results for only the wires containing chevron indents (nine wires). Each pullout force value in the table and point on the graphs represent the average of the six individual maximum pullout forces measured at end slips less than or equal to 0.10 in. of end slip at KSU. Each transfer length value in the table and point on the graphs represent the average of the 50 transfer lengths measurements obtained at CXT. The R^2 is the correlation between these two averaged data sets.

Table 7.2 As-received wires, KSU pullout forces vs. CXT transfer lengths

As-Received Wire Bond Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
Maximum Pullout Force (ES ≤ 0.10 in.)

Wire	KSU Avg. Pullout Force (n = 6)[1] (lbf)	Std. Dev. (lbf)	C.V. (%)	CXT Avg. Transfer Length[2] (n ≈ 50)[1] (in.)
[WA]	427	24	5.6	14.3
[WB]	6481	570	8.8	10.2
[WC]	7646	967	12.6	11.2
[WD]	5555	357	6.4	9.7
[WE]	7674	526	6.9	8.6
[WF]	8312	459	5.5	7.8
[WG]	5505	385	7.0	10.9
[WH]	7605	497	6.5	8.3
[WI]	6567	522	8.0	10.8
[WJ]	7034	635	9.0	9.4
[WL]	2068	322	15.6	13.3
[WM]	6879	503	7.3	9.2

Note 1: n = Sample size used to obtain the average value
Note 2: Bilinear surface strain profile assumed

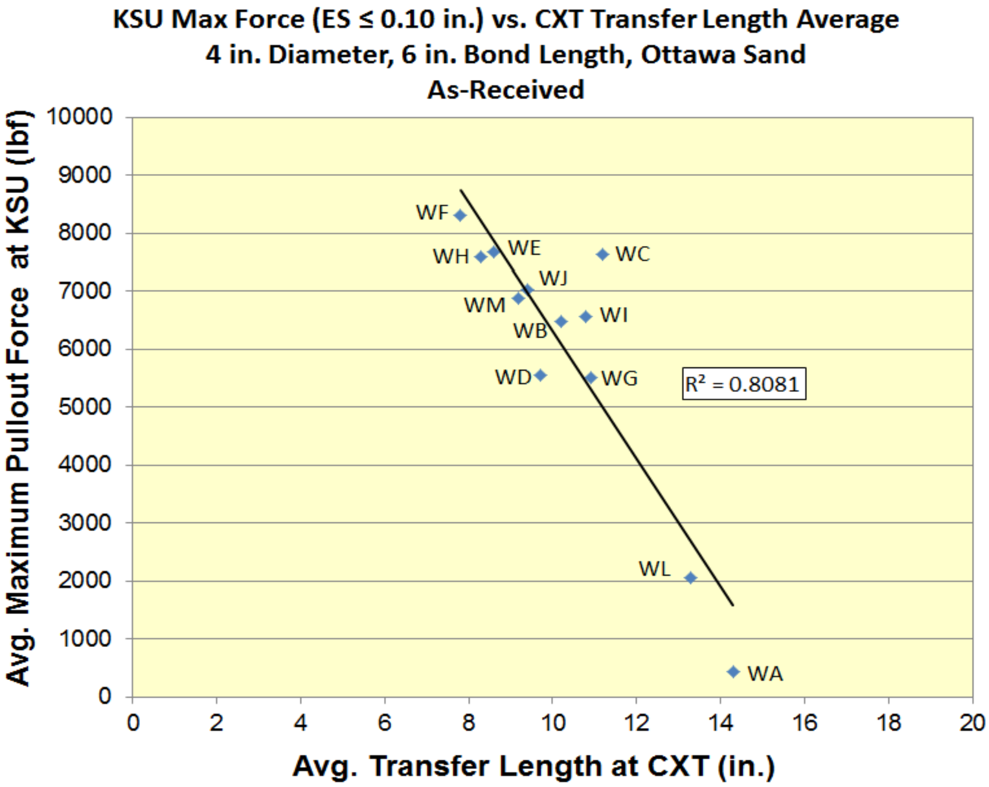


Figure 7.15 As-received wires, KSU pullout forces vs. CXT transfer lengths

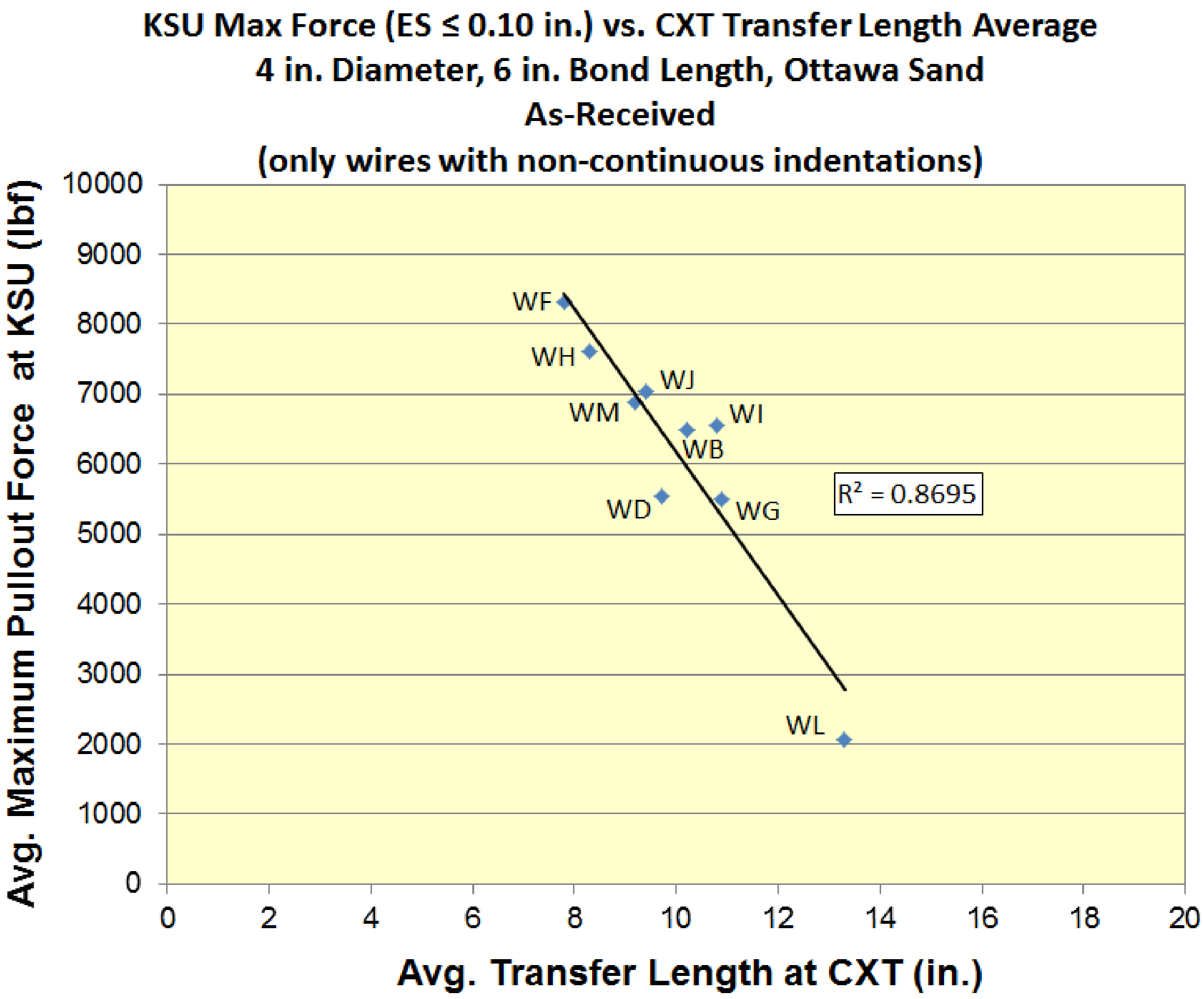


Figure 7.16 As-received wires, KSU pullout forces vs. CXT transfer lengths (individual-indents only)

For the data set including all 12 wires, a correlation of $R^2 = 0.808$ was achieved. For the data sets containing only the chevron-indented wires (nine wires), a correlation of $R^2 = 0.870$ was achieved. Both of these values show extremely good correlation between the pullout tests performed in mortar at the KSU laboratory and the transfer lengths obtained from actual concrete railroad ties produced at CXT.

Based on this analysis, the answer to the question “Can a quality control wire pullout test performed in a lab be used to predict the actual measured transfer lengths produced at a plant?” is “Yes.” The regression analysis using only wires with non-continuous indentations (nine-wire set) can be used to predict the transfer length of concrete railroad ties using other wire sources conforming to ASTM C881. This set of data was used because at present, the spiral and smooth wires are not permitted to be used in prestressed concrete railroad tie production in the United States. The model generated by this data set is shown in Figure 7.17 and is the same data used to obtain Figure 7.16 above Equation 7.1 obtained from the model in Figure 7.17 gives the equation of the expected transfer length of as-received, indented prestressing wires when used in concrete railroad ties. The maximum force value input into this equation shall be obtained using the wire pullout test described in Appendix I.

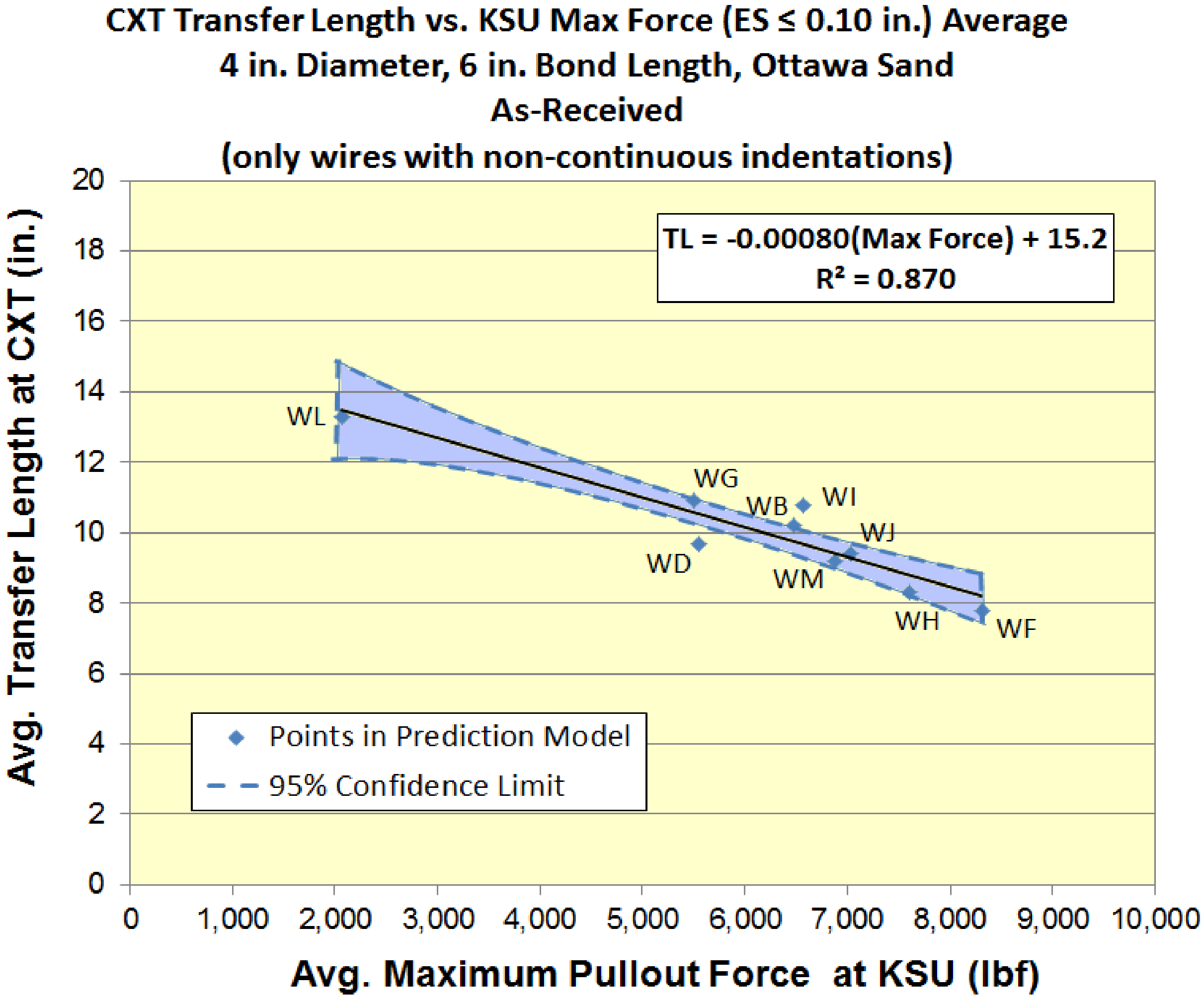


Figure 7.17 As-received wires, transfer length prediction model in concrete

$$\boldsymbol{TL = -0.00080(Max\ Force) + 15.2} \qquad \text{Equation 7.1}$$

where TL = expected transfer length in concrete railroad ties using pretensioned wires

$Max\ Force$ = maximum force ≤ 0.10 in. end slip

7.2 Comparison of Strand Data

7.2.1 Procedural Differences between Lab and Plant, Strand

There are a number of procedural similarities and differences between the strand pullout tests performed in the lab at Kansas State University (KSU) and the strand pullout tests performed in the plant at CXT Concrete Ties (CXT).

There are two main similarities between the lab and plant phases. First, both tests were un-tensioned. Second, force was applied at the bottom of the specimen and an LVDT was placed on the top of the specimen to measure the free end slip in both testing locations.

Numerous differences exist between the two pullout tests performed on strands. First, mortar was used during the lab pullout tests at KSU and concrete was used during the plant pullout tests at CXT. This was a planned research variable. Second, specimen sizes at both locations were very different. The two specimen sizes at KSU were both 5-in.-outer-diameter. The first standard specimen length was 18 in. total length and 16 in. bond length. The second, modified specimen length was 12 in. total length and 16 in. bond length. The schematic of the two specimen sizes at KSU can be seen in Figure 5.1 and Figure 5.2, respectively. The specimens at CXT utilized a 4-in.-inner-diameter steel tube with a total length of 8 in. Within the 8-in.-long steel tube, there was a 4-in. bond length. The schematic of the specimens used at CXT can be seen in Figure 6.2. Another difference – albeit an unplanned, but unavoidable one – was the strength at which each pullout test was performed. Pullout tests performed at KSU were tested with mortar batches consistently around 4500 psi. Pullout tests performed at CXT were tested with concrete batches that fluctuated in strength. This variation in strength occurred because the pullout tests at CXT were performed at approximately the same time as the railroad ties were de-tensioned (to be used to take transfer length measurements). The average mortar and concrete strengths for each set of KSU strand pullout tests and the CXT pullout tests can be seen in Table 7.4 and Table 7.5, respectively. Fourth, the specimens run at KSU were run in displacement control at a constant rate of 0.1 in./min. Specimens at CXT were force controlled with a loading rate of approximately 1800-2100 pounds/min. The KSU tests were able to remain at a constant loading rate due to the servo-hydraulic actuator and computer software, which precisely controlled the hydraulic fluid levels. The CXT tests were run in a Forney testing machine in which the small hydraulic pump could only be manually controlled using a screw-type valve. The last major difference between the two testing sites was the curing methodology. The pullout specimens and mortar cubes used to test the compressive strength at KSU were stored for curing in a temperature- and moisture-controlled room. Details of this curing methodology can be found in Section 5.2.4. The pullout specimens and 4-in. x 8-in. cylinders used to test the compressive strength at CXT were stored in a temperature-controlled closet, but were not humidity controlled. Details of this curing methodology can be found in Section 6.2.3.

7.2.2 As-Received Strand Results

This section presents the results of the as-received strand pullout specimens performed at KSU and at CXT. Three of the six strands used in this study were tested both at KSU and at CXT. SA, SB and SC were all tested at both testing locations. SA and SB are both 3/8-in.-diameter, seven-wire strands. SC is a 5/16-in.-diameter, three-wire strand. SA and SC are both smooth strands whereas SB is indented.

Due to an error that took place in the plant, pullout specimens at CXT containing strand SB were tested using a 6-in. bond length instead of the 4-in. bond length used for strands SA and SC. Furthermore, specimens at KSU had two varying bond lengths as well (16 in. and 9 in.) that will need to be correlated with. Because of the different bond lengths of the specimens, bond stress was used for direct comparison of pullout results instead of pullout force. Bond stress is defined as the pullout force at any location divided by the total surface area in contact with the mortar or concrete. This surface area is mathematically defined as the perimeter of the strand multiplied by the bond length. Table 7.3 contains the bond area for strands SA, SB, and SC. All pullout forces from this point forward will be divided by the respective bond areas.

Average bond stress vs. end slip graph for each strand source is shown in Figure 7.18 through Figure 7.20. Each “KSU average” and “CXT average” line on the graphs represents the average of six individual specimens from the same wire source, except for the SC data set at CXT which is represented by four specimens. The reduced numbers of specimens is a result of malfunctions with the LVDT and data acquisition software while at CXT. Results of the individual pullout tests comparing six KSU specimens to six CXT specimens for each wire source can be seen in Appendix O.

Table 7.3 Bond areas of different bonded strand lengths

Strand Idnetification	[SA]	[SB]	[SC]
Indentation Type	3/8" 7-Wire, Smooth	3/8" 7-wire, Indented	5/16" 3-wire, Smooth
Cross-Sectional Area (in^2)	0.0850	0.0850	0.0582
Perimeter Length (in.)	1.378	1.378	2.138
16 in. Long Bond Area (in^2)	22.048	22.048	34.208
9 in. Long Bond Area (in^2)	12.402	12.402	19.242
6 in. Long Bond Area (in^2)	8.268	8.268	12.828
4 in. Long Bond Area (in^2)	5.512	5.512	8.552

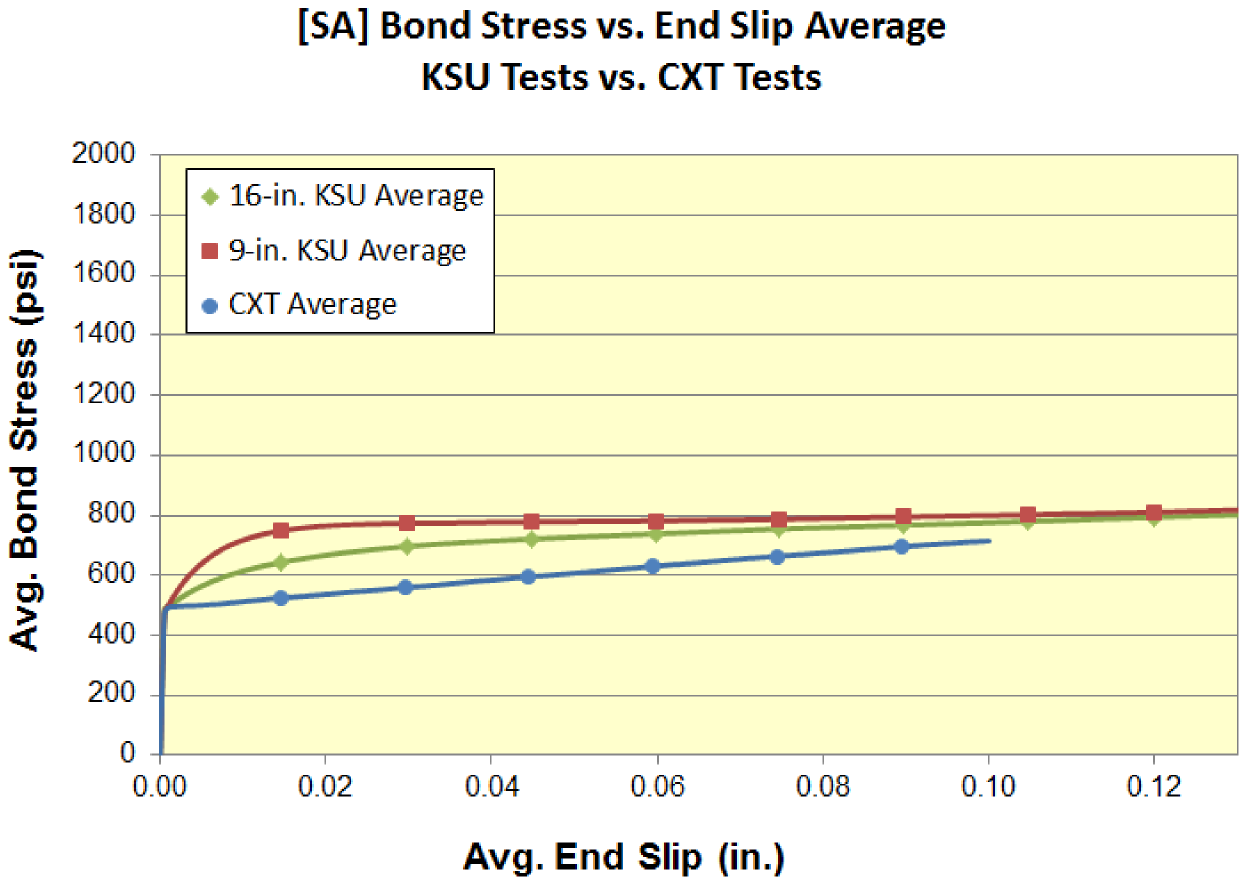


Figure 7.18 [SA] bond stress vs. end slip average graphs, KSU vs. CXT

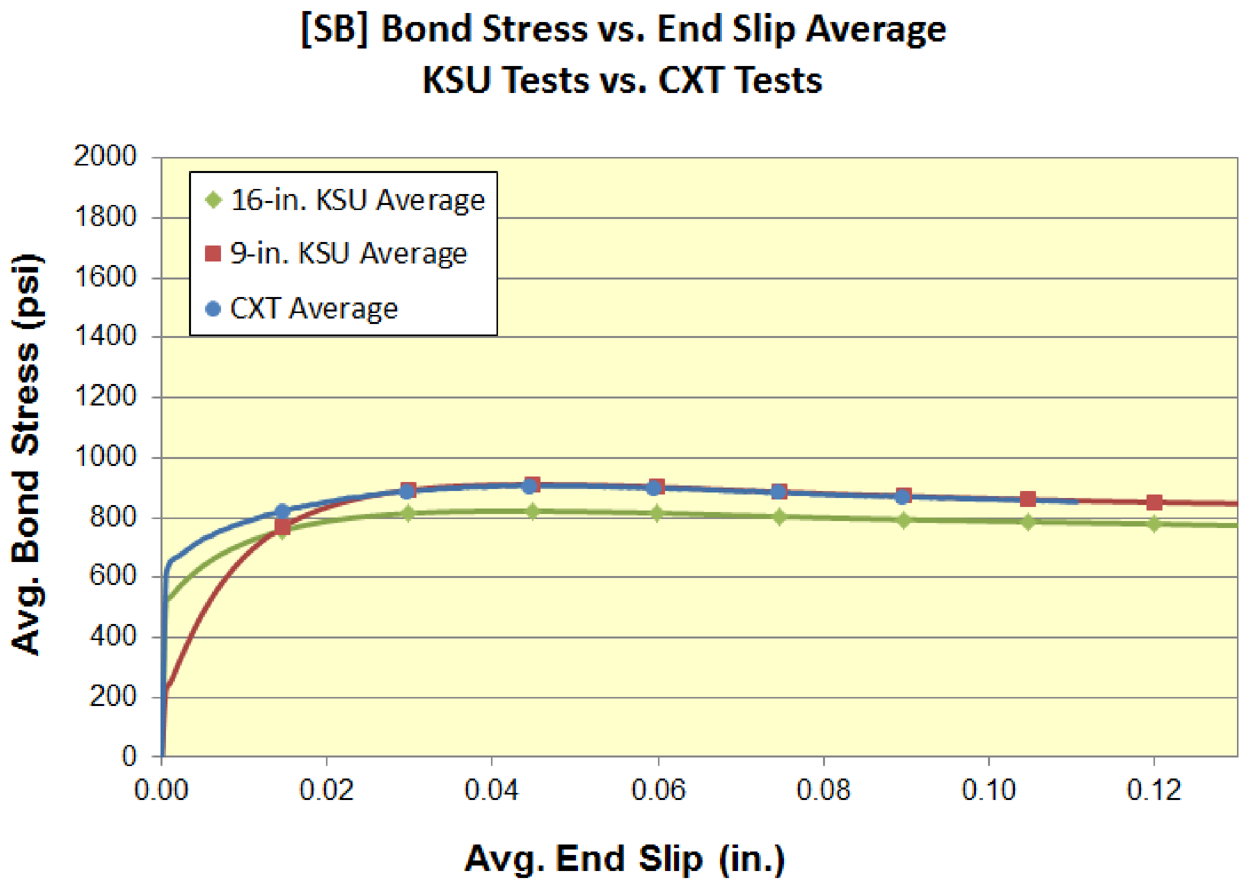


Figure 7.19 [SB] bond stress vs. end slip average graphs, KSU vs. CXT

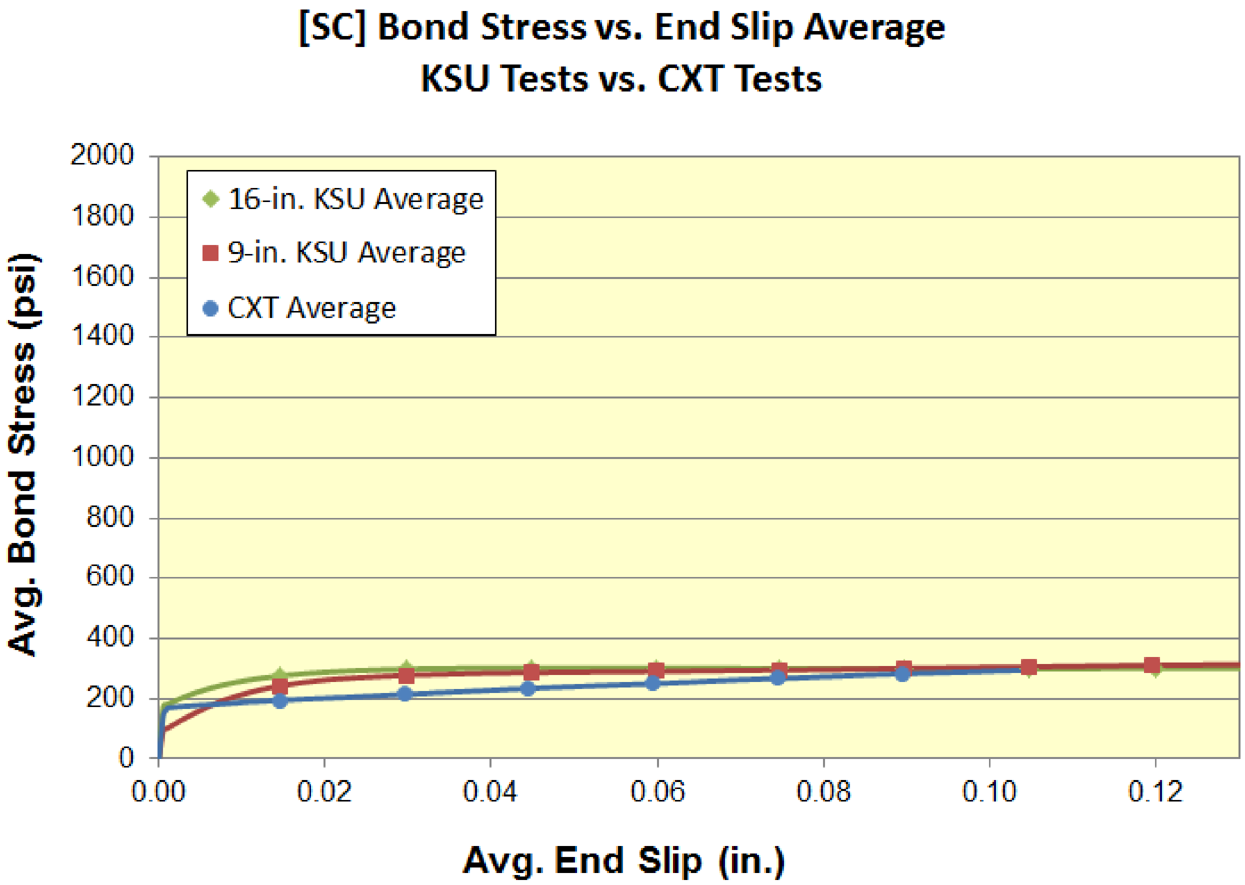


Figure 7.20 [SC] bond stress vs. end slip average graphs, KSU vs. CXT

7.2.3 Analysis of KSU Pullout Tests vs. CXT Pullout Tests

All methods of analysis in this section compare results from Section 5.3.1 (as-received strand pullout data at KSU) to results from Section 6.3.2 (as-received strand pullout data obtained at CXT). The bond stress derived from the pullout force obtained at 0.10 in. of end slip was used to compare the KSU and CXT data sets. Due to the vastly different bond lengths, the bond stress of each strand source was again used in place of pullout force for the direct comparison of pullout results. CXT results were compared to both the 16-in. bond length KSU tests and the 9-in. bond length KSU tests.

Analysis of the16-in. bond length KSU specimens compared to the CXT results are presented in Table 7.4 and include average bond stress, standard deviations, coefficient of variations (C.V.), and average mortar/concrete strengths at the time of testing for both KSU and CXT data sets. The data is also represented graphically in Figure 7.21. The same data is presented for the KSU specimens with 9-in. bond length in Table 7.5 and Figure 7.22.

Each value in the tables and each point on the graphs represents the average of the individual bond stress values. The bond stress values were obtained from the pullout forces which caused 0.10 in. of end slip divided by the bond area (strand perimeter multiplied by the bond length). The x-axis shows these bond stresses taken from CXT pullout tests. The y-axis shows these bond stresses obtained from KSU pullout tests. The R^2 is the correlation between these two averaged data sets.

The “Perfect Test” line represents the data of a fictional test in which the bond stress at KSU was identical to the bond stress at CXT for all pullout tests. “The nearness of the data to the ‘perfect line’ is an indicator of whether the test is repeatable and reproducible between test sites” (Russell and Paulsgrove, 1999b). The tests performed at KSU and CXT are fundamentally different (one being in mortar, the other in concrete), but the “Perfect Test” line still gives some insight into the similarities and differences between the two tests.

From Table 7.4 and Table 7.5, it can be seen that results from KSU and the bond stress results from CXT are extremely similar. The bond stresses from both sites showed similar scatter. The average coefficients of variation (C.V.) were 11.0%, 8.3%, and 15.5% for values obtained for the 16-in. KSU specimens, 9-in. KSU specimens and CXT specimens, respectively.

When the 16-in. bond length specimens from KSU were compared with the CXT specimens, a correlation of $R^2 = 0.949$ was achieved. When the 9-in. bond length specimens from KSU are compared with the CXT specimens, a correlation of $R^2 = 0.7979$ was achieved. Both of these values show an almost perfect correlation for the two different testing methodologies, especially considering the tests at KSU were performed in mortar and the tests at CXT were performed in concrete (and the concrete had relatively variable strengths). Additionally, the orientations of the actual test results to the “Perfect Test” lines indicate the two tests are almost identical, repeatable, and reproducible. These regression values must be viewed in context, however. With only three strands in this analysis, it is hard to draw any deeply meaningful conclusions.

Another point of interest is the point of first slip. This point can be seen in Figure 7.18 through Figure 7.20 as the force at which end slip begins to occur. Since the LVDT is taking readings at the opposite end from the applied force, it does not record any readings until the cohesion and/or mechanical interlock along the entire length of the wire is broken. In mortar, the point of first slip is assumed to occur after cohesion alone is overcome. For concrete, the point of first slip is assumed to occur after both cohesion and mechanical interlock between the steel and aggregates is overcome. For strands SA and SC, however, the point of first slip for all three specimen sizes (two KSU and one CXT) was approximately the same. SB was more variable. The 16-in. bond length KSU and CXT specimens slipped at an almost identical bond stress, but the 9-in. bond length KSU specimen started slipping sooner for all six SB tests at that length. This data lends to the idea that the first slip response of strands is similar for both mortar and concrete.

Table 7.4 As-received strands, bond stress data at 0.10 in. end slip, 16 in. KSU vs. CXT

As-Received Strand Pullout Test Results Bond Stress at 0.10 in. End Slip								
	KSU Test Data 16 in. Bond Length, Mortar (sample size = 6)				CXT Test Data 4 in. Bond Length^2, Concrete (sample size = 6, SC = 4)			
Strand	Bond Stress (psi)	Std. Dev. (psi)	C.V. (%)	Avg. Mortar Strength^1 (psi)	Bond Stress (psi)	Std. Dev. (psi)	C.V. (%)	Concrete Strength (psi)
[SA]	776	47	6.0	4602	715	100	14.0	5924
[SB]	789	63	8.0	4602	862	31	3.6	6536
[SC]	300	57	19.1	4602	291	85	29.0	6607

Note 1: Each of the six specimens at KSU were cast in a different batch of mortar and averaged.
The mortar strength of 4602 psi is the average of all six batches.

Note 2: Strand [SB] was accidentally tested with a 6 in. bond length. This was corrected for in the bond stress calculation.

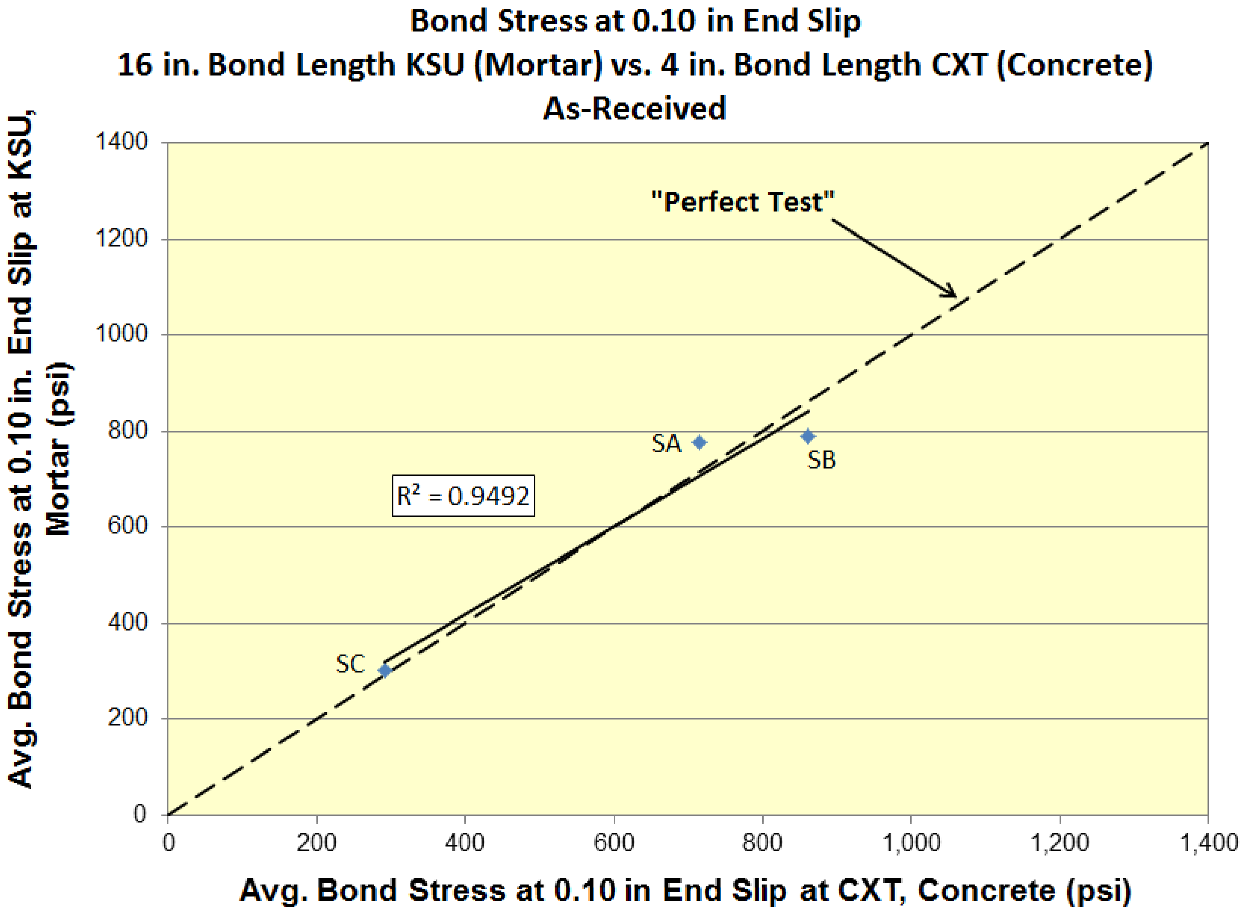


Figure 7.21 As-received strands, bond stress data at 0.10 in. end slip, 16 in. KSU vs. CXT

Table 7.5 As-received strands, bond stress data at 0.10 in. end slip, 9 in. KSU vs. CXT

As-Received Strand Pullout Test Results Bond Stress at 0.10 in. End Slip								
	KSU Test Data 9 in. Bond Length, Mortar (sample size = 6)				CXT Test Data 4 in. Bond Length[2], Concrete (sample size = 6, SC = 4)			
Strand	Bond Stress (psi)	Std. Dev. (psi)	C.V. (%)	Mortar Strength[1] (psi)	Bond Stress (psi)	Std. Dev. (psi)	C.V. (%)	Concrete Strength (psi)
[SA]	800	95	11.8	4655	715	100	14.0	5924
[SB]	864	39	4.6	4655	862	31	3.6	6536
[SC]	304	26	8.4	4655	291	85	29.0	6607

Note 1: Each of the six specimens at KSU were cast in a different batch of mortar and averaged. The mortar strength of 4655 psi is the average of all six batches.

Note 2: Strand [SB] was accidentally tested with a 6 in. bond length. This was corrected for in bond stress calculation.

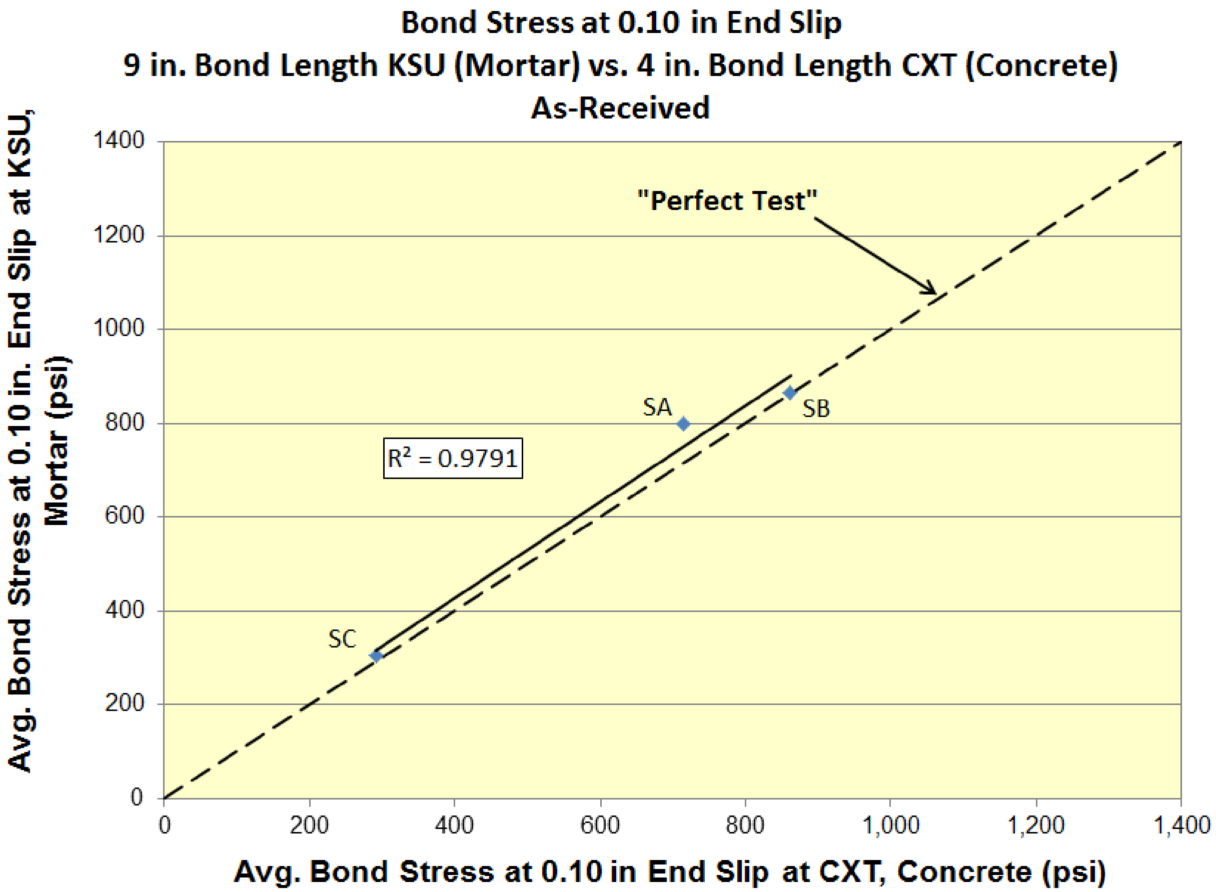


Figure 7.22 As-received strands, bond stress data at 0.10 in. end slip, 9 in. KSU vs. CXT

7.2.4 Analysis of KSU Pullout Tests vs. CXT Transfer Length Measurements

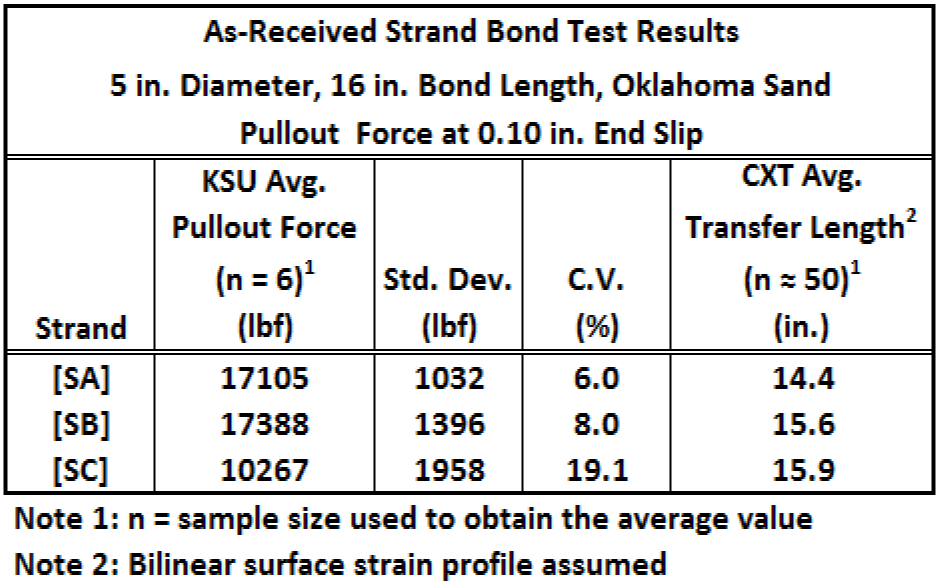
The analysis presented in this section compares the results from Section 5.3.1 (as-received strand pullout data at KSU) to the results from Section 6.3.3 (as-received transfer length measurements obtained at CXT). The CXT results were compared to both the 16-in. bond length KSU tests and the 9-in. bond length KSU tests.

This analysis is the capstone of the strand bond testing program as a quality control test. With interest from the railroad industry to use small diameter (less than 0.5 in.) strands in concrete railroad ties, this analysis aims to answer an important question for the industry: “Can an un-tensioned quality control strand pullout test performed in a lab be used to predict the actual measured transfer lengths produced at a plant?” The desire is to be able to test small samples of the strand in a relatively cheap quality control test and be able to use those test results to predict the bond quality (and transfer length) of actual concrete railroad ties with relative certainty. This section aims to answer that question exactly.

A coefficient of determination (R^2) value was calculated by comparing the pullout force measured at KSU to the transfer lengths measured at CXT. A pullout force corresponding to 0.10 in. of end slip was used. These pullout forces were obtained from un-tensioned pullout tests in mortar performed at Kansas State University. The pullout tests follow the testing methodology and protocol set forth in Appendix H of NCHRP Repot 603 (Ramirez and Russell, 2008). The transfer lengths were obtained from actual pretensioned concrete railroad ties cast at CXT Concrete Ties in Tucson, Ariz.

The correlation was found for 1) the 16-in. bond length KSU specimens and 2) the 9-in. bond length KSU specimens. Results of the average pullout force at 0.10 in. of end slip compared with the average transfer lengths can be seen in Table 7.6 and Figure 7.23 for the 16-in. bond length KSU specimens. Table 7.7 and Figure 7.24 show the 9-in. bond length KSU specimen results. Each pullout force value in the table and point on the graphs represent the average of six individual pullout forces measured at 0.10 in. of end slip at KSU. Each transfer length value in the table and point on the graphs represent the average of the 50 transfer length measurements obtained at CXT. The R^2 is the correlation between these two averaged data sets.

Table 7.6 As-received strands, KSU pullout forces vs. CXT transfer lengths (16 in. bond)



As-Received Strand Bond Test Results

5 in. Diameter, 16 in. Bond Length, Oklahoma Sand

Pullout Force at 0.10 in. End Slip

Strand	KSU Avg. Pullout Force (n = 6)[1] (lbf)	Std. Dev. (lbf)	C.V. (%)	CXT Avg. Transfer Length[2] (n ≈ 50)[1] (in.)
[SA]	17105	1032	6.0	14.4
[SB]	17388	1396	8.0	15.6
[SC]	10267	1958	19.1	15.9

Note 1: n = sample size used to obtain the average value

Note 2: Bilinear surface strain profile assumed

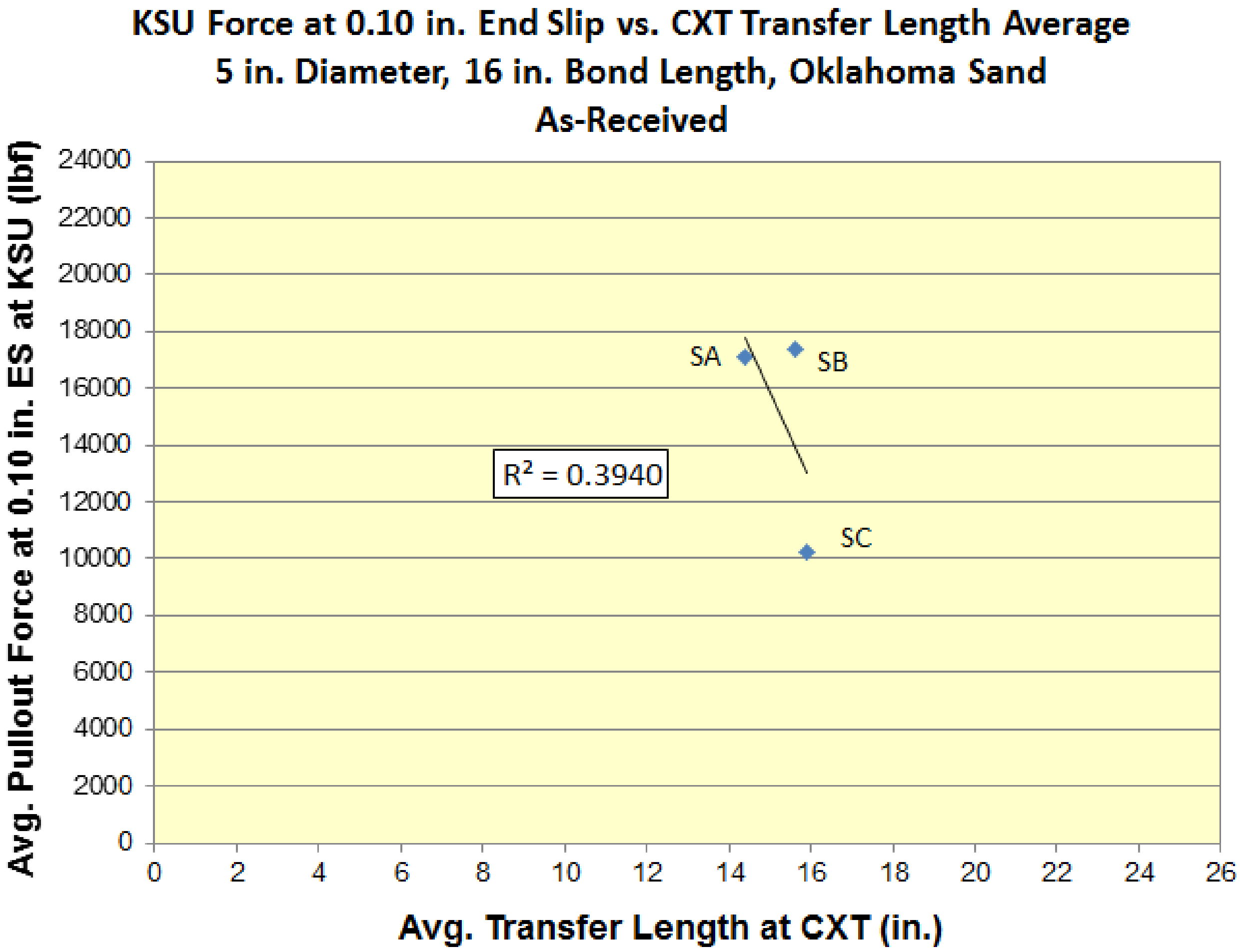


Figure 7.23 As-received strands, KSU pullout forces vs. CXT transfer lengths (16 in. bond)

Table 7.7 As-received strands, KSU pullout forces vs. CXT transfer lengths (9 in. bond)

As-Received Strand Bond Test Results
5 in. Diameter, 9 in. Bond Length, Oklahoma Sand
Pullout Force at 0.10 in. End Slip

Strand	KSU Avg. Pullout Force (n = 6)[1] (lbf)	Std. Dev. (lbf)	C.V. (%)	CXT Avg. Transfer Length[2] (n ≈ 50)[1] (in.)
[SA]	9918	1173	11.8	14.4
[SB]	10718	489	4.6	15.6
[SC]	5852	491	8.4	15.9

Note 1: n = sample size used to obtain the average value
Note 2: Bilinear surface strain profile assumed

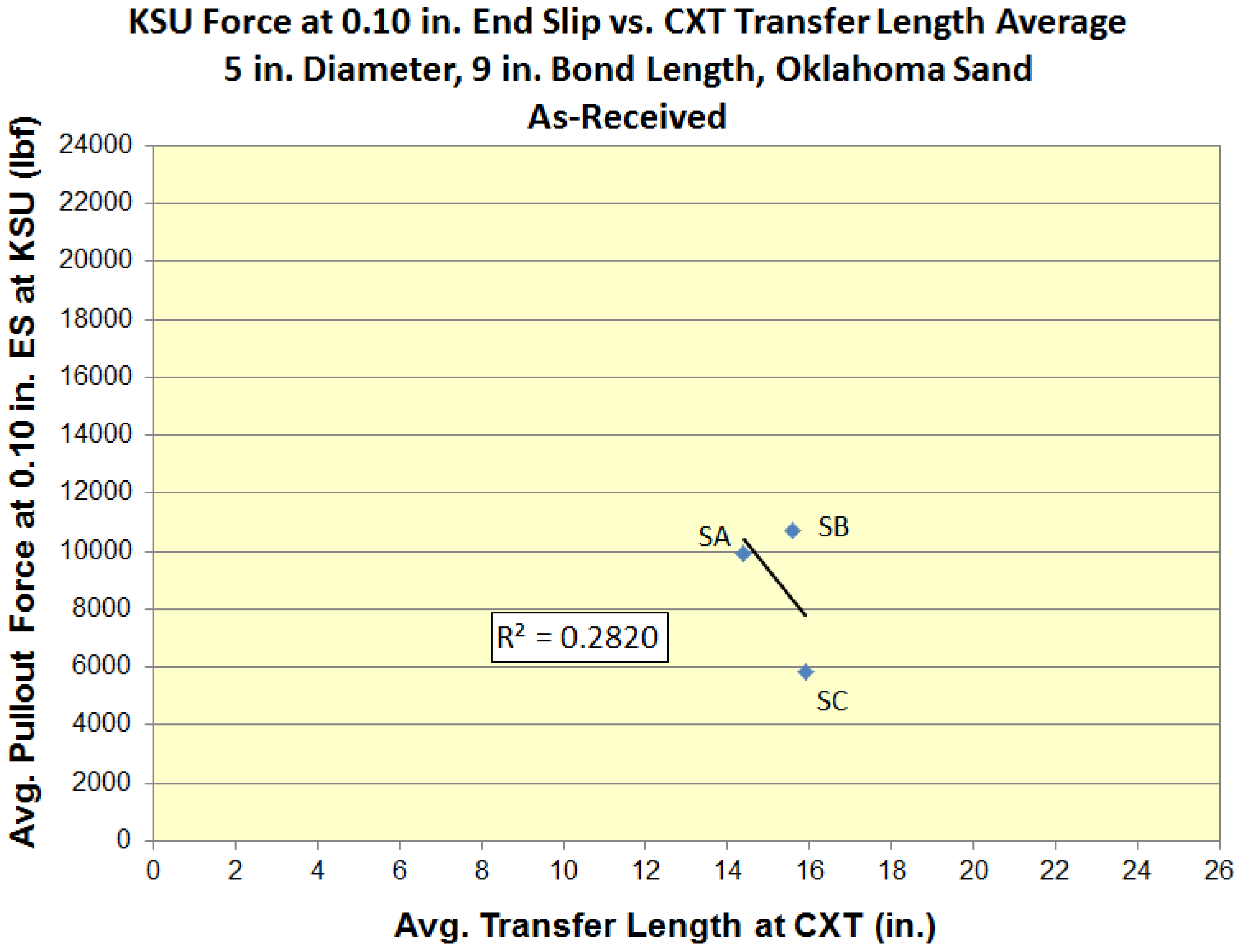


Figure 7.24 As-received strands, KSU pullout forces vs. CXT transfer lengths (9 in. bond)

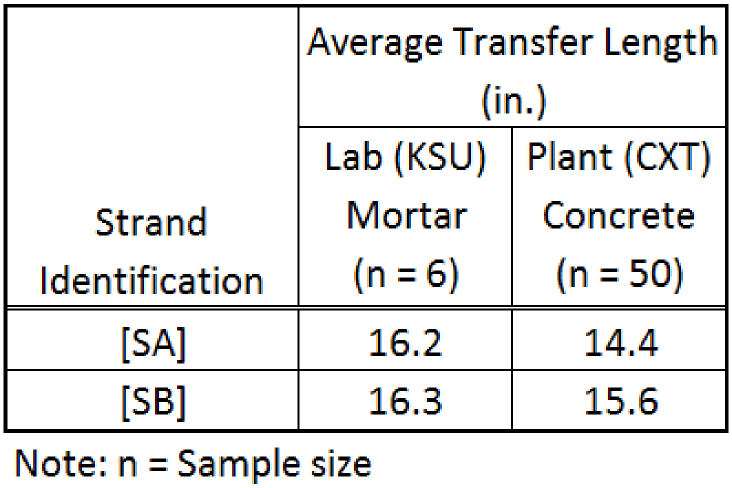
For the 16-in. bond length data set, a correlation of $R^2 = 0.394$ was achieved. For the 9-in. bond length data set, a correlation of $R^2 = 0.282$ was achieved. Both of these values show poor correlation between the pullout tests performed in mortar at the KSU laboratory and the transfer lengths obtained from actual concrete railroad ties produced at CXT.

Based on this limited analysis, the answer to the question “Can an un-tensioned quality control strand pullout test performed in a lab be used to predict the actual measured transfer lengths produced at a plant?” is “Not at this time.” Again, due to the limited number of strands used to generate these results, these regression values must be viewed in context. With only three strands in this analysis, it is hard to draw any deeply meaningful conclusions.

Recalling the as-received transfer lengths of the strands obtained in the lab from Section 5.3.3, it appears some surface condition factors could also be at work which have not been accounted for. In the lab, strand SB and strand SA performed almost identically despite strand SA having a moderate level of surface rust. This alone was odd since strand SB had indentations and strand SA did not. However, it was determined in Section 5.3.5 that the surface condition of the strand was an important parameter based on the results of the cleaning process.

In the plant, however, strand SA vastly outperformed strand SB. This lends to the notion that the specimens tested in the lab (at KSU) might have had different surface conditions than the specimens tested in the plant (at CXT). The average transfer length from both the lab and plant phases can be seen in Table 7.8.

Table 7.8 Transfer length differences between lab and plant



Strand Identification	Average Transfer Length (in.)	
	Lab (KSU) Mortar (n = 6)	Plant (CXT) Concrete (n = 50)
[SA]	16.2	14.4
[SB]	16.3	15.6

Note: n = Sample size

Chapter 8 - Conclusions and Recommendations

8.1 Conclusions

Five conclusions can be drawn concerning development of the wire bond test and subsequent results and analysis:

1. The un-tensioned wire pullout test developed at Kansas State University and presented in Chapter 4 was able to distinguish between higher and lower bonding wires. This is supported by results from Section 4.3.1. The testing methodology is summarized in Appendix I.
2. This un-tensioned wire pullout test yielded consistent pullout strength results when six different mortar batches were used. The repeatability of these results is shown by the individual pullout graphs presented in Appendix E.
3. This un-tensioned wire pullout test had excellent correlation with the bond performance of the wires in pretensioned applications. The most accurate correlation with transfer lengths of the pullout test values came by reporting the maximum pullout force occurring at or before 0.10 in. of free-end slip. This method of analysis yielded a correlation value (R^2) equal to 0.882 when all 12 wires were considered. An $R^2 = 0.916$ was achieved when only considering the nine wires with non-continuous indentations. These results can be seen in Section 4.3.4.1.
4. The un-tensioned wire pullout test described in Appendix I was able to accurately predict the transfer length of a previously untested wire. Using results of the regression analysis, a predictive model for transfer lengths using pretensioned wires is given in Section 4.3.5. This equation (Equation 4.1) was able to predict the transfer length of a previously untested wire to within 0.1-in. accuracy. The measured (experimental) transfer length was found to be 9.8 inches and the predicted (theoretical) transfer length was found to be 9.9 inches.
5. There was not a consistent bond quality for wires having the same general indent pattern (i.e. all “chevrons” do not bond approximately the same).

Three conclusions were made concerning the Standard Test for Strand Bond validity for smaller diameter strands:

1. The Standard Test for Strand Bond caused some of the smaller diameter strands (less than 0.5-in.-diameter) to fail in material rupture rather than bond failure. This was caused by too long of a bonded length.
2. The Standard Test for Strand Bond can be used in its entirety for smaller diameter strands by shortening the bond length to 9 in. and the overall specimen length to 12 in. With this shorter bonded length, none of the specimens failed by material rupture.
3. The Standard Test for Strand bond had decent-to-good correlation with measured transfer lengths when only the five strands with 3/8-in.-diameter are considered. For the 16-in. bond length specimens, an $R^2 = 0.852$ was achieved. For the 9-in. bond length specimens, an $R^2 = 0.573$ was achieved. When all six strands were considered, no statistical correlation was found between the pullout results and measured transfer lengths. These results can be seen in Section 5.3.4.

Two related conclusions concerning surface condition can be drawn from comparing the as-received pullout results to the cleaned pullout results:

1. The surface condition of prestressing wires is not the dominant bond characteristic. Rather, the indent geometry plays a much larger role. Since the area of the wire indents is large relative to the overall cross-sectional area of the 5.32 mm-diameter wire, the indent geometry governs the overall bond performance of the wires.
2. The surface condition of prestressing strands is a very important bond characteristic. Since the area of the strand indents is smaller relative to the overall cross-sectional area of the 5/16 in.-diameter and 3/8 in.-diameter strands (than the ratio for 5.32-mm-diameter wires), the indent geometry plays a smaller role in the overall bond performance of the strands and the surface condition contributes a much more meaningful portion to the overall bond performance of the strands. This conclusion is also supported by 1) Rose and Russell (1997) and 2) Barnes, Grove, and Burns (2003) for seven-wire, 0.5-in.-diameter strands and by Gustavson (2004) for a three-wire, 6.5-mm-diameter strands.\

Six conclusions can be drawn when comparing lab data using mortar to plant data using concrete:

1. Wire pullout tests performed in mortar had very good correlation with transfer lengths measured from actual concrete railroad ties. A correlation value (R^2) equal to 0.808 was achieved when all 12 wires were considered. An $R^2 = 0.870$ was achieved when only considering the nine wires with non-continuous indentations. These results can be seen in Section 7.1.4.
2. Based on the excellent correlation between wire pullouts in mortar and transfer lengths measured from actual concrete railroad ties, Equation 7.1 of Section 7.2.4 is given to predict the transfer length of concrete railroad ties using prestressed wires.
3. Maximum force for the wire tests performed in mortar generally occurred at a higher end slip value than the maximum forces for the tests performed in concrete. Despite the maximum force *value* being similar for most wire sources, *location of this maximum value* occurred at a higher end slip value in mortar compared with concrete. This trend can be seen for each wire source in Figure 7.1 through Figure 7.12.
4. Strand pullout tests performed in mortar had poor correlation with the transfer lengths measured from actual concrete railroad ties. A correlation value (R^2) equal to 0.394 was achieved using the standard length (16-in. bond length) specimens. An $R^2 = 0.282$ was achieved using the modified length (9-in. bond length) specimens. These results can be seen in Section 7.2.4.
5. The bond stress for strand pullouts cast in mortar and in concrete all follow almost identical force vs. end slip curves, even for three different bond lengths (16 in., 9 in., and 4 in.). This trend can be seen in Figure 7.18 through Figure 7.20.
6. For both wires and strands, the pullout tests performed in mortar and in concrete yielded similar results. These results are shown in Sections 7.1.3 and 7.2.3 for wires and strands, respectively.

8.2 Recommendations

Based on the previous conclusions, five recommendations are made about the future wire bond testing:

1. The test result of the wire bond test should be taken as the maximum load recorded at a free-end slip less than or equal to 0.10 in. This method of analysis proved to have the best correlation with measured transfer lengths.
2. While the current research established the un-tensioned pullout test presented herein is quite repeatable (when using different mortar batches), the author recommend the wire pullout test be conducted at other locations to establish the reproducibility of test results. Preferably, this would be done in a round-robin (blind-to-the-tester) style program.
3. Once the reproducibility of the wire pullout test is established, threshold values for acceptance could be recommended and the test be adopted as a quality control standard to provide a minimum bond quality of prestressing wires used in railroad tie applications.
4. The testing methodology of Appendix I should be considered as a specification for the bond of prestressing wires after the testing described in the second recommendation has been performed.
5. Equation 7.1 (shown in Section 7.1.4), along with results of the pullout test described in Appendix I, should be used as a preliminary means for estimating the transfer length of concrete railroad ties using similar mix designs, release strengths, and pretensioned non-continuously indented wires.

The author make two recommendations concerning the strand tests performed on smaller diameter strands:

1. Further testing at other locations using the “modified” Standard Test for Strand Bond should be conducted with smaller diameter strands and a 9-in. bond length. This will help establish the reproducibility of test results. Preferably, this would be done in a round-robin (blind-to-the-tester) style program.
2. Once the reproducibility of the “modified test for strand bond” is established or refuted for smaller diameter strands, then threshold values for acceptance could be recommended and the test be adopted as a quality control standard to provide a minimum bond quality of small diameter prestressing strands used in railroad tie applications.

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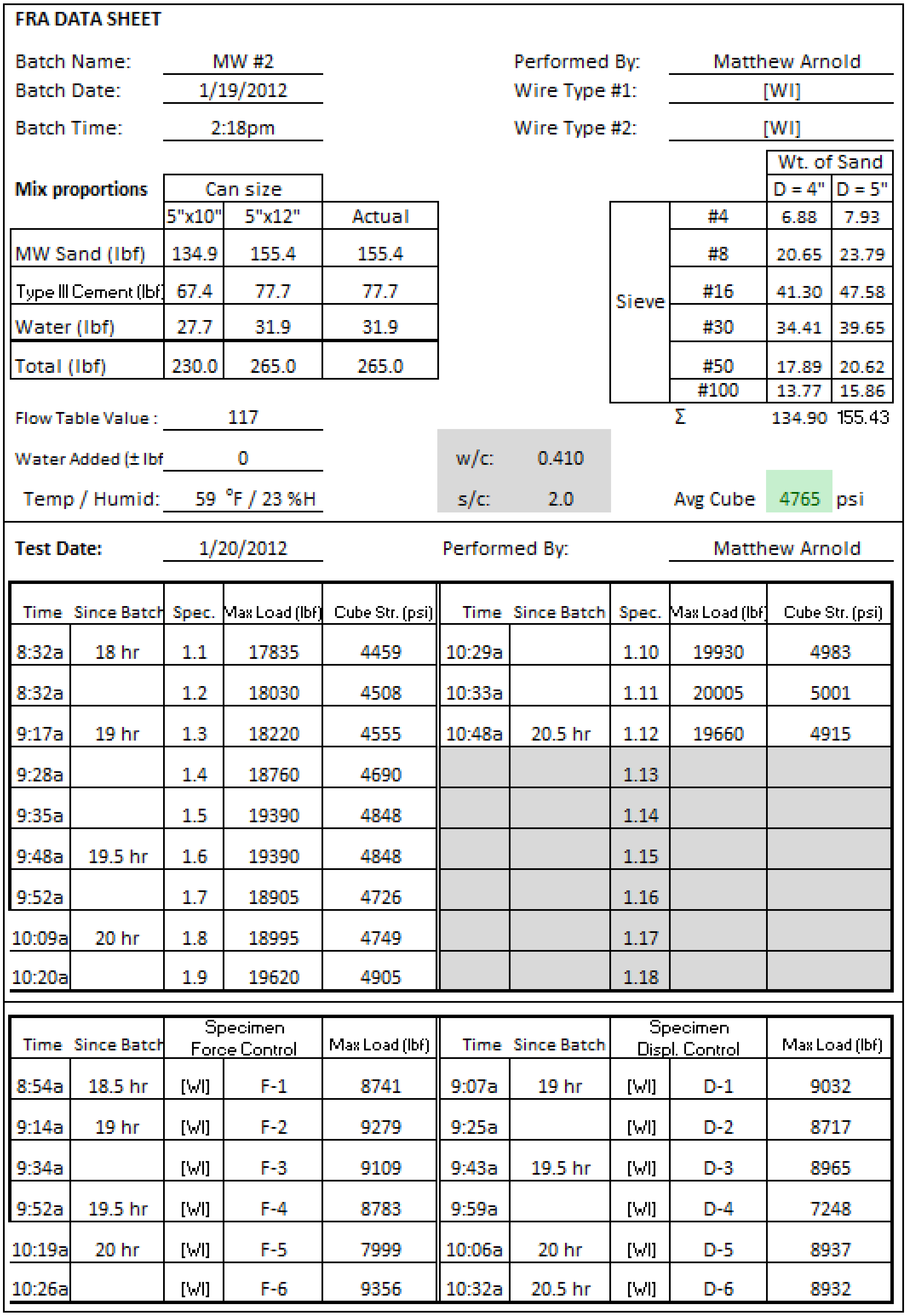
Appendix A - Lab Phase, Wire; Test Development Batch Summaries



FRA DATA SHEET

Batch Name: MW #2
Batch Date: 1/19/2012
Batch Time: 2:18pm

Performed By: Matthew Arnold
Wire Type #1: [WI]
Wire Type #2: [WI]

Mix proportions	Can size		
	5"x10"	5"x12"	Actual
MW Sand (lbf)	134.9	155.4	155.4
Type III Cement (lbf)	67.4	77.7	77.7
Water (lbf)	27.7	31.9	31.9
Total (lbf)	230.0	265.0	265.0

		Wt. of Sand	
		D = 4"	D = 5"
Sieve	#4	6.88	7.93
	#8	20.65	23.79
	#16	41.30	47.58
	#30	34.41	39.65
	#50	17.89	20.62
	#100	13.77	15.86
	Σ	134.90	155.43

Flow Table Value : 117
Water Added (± lbf: 0
Temp / Humid: 59 °F / 23 %H

w/c: 0.410
s/c: 2.0

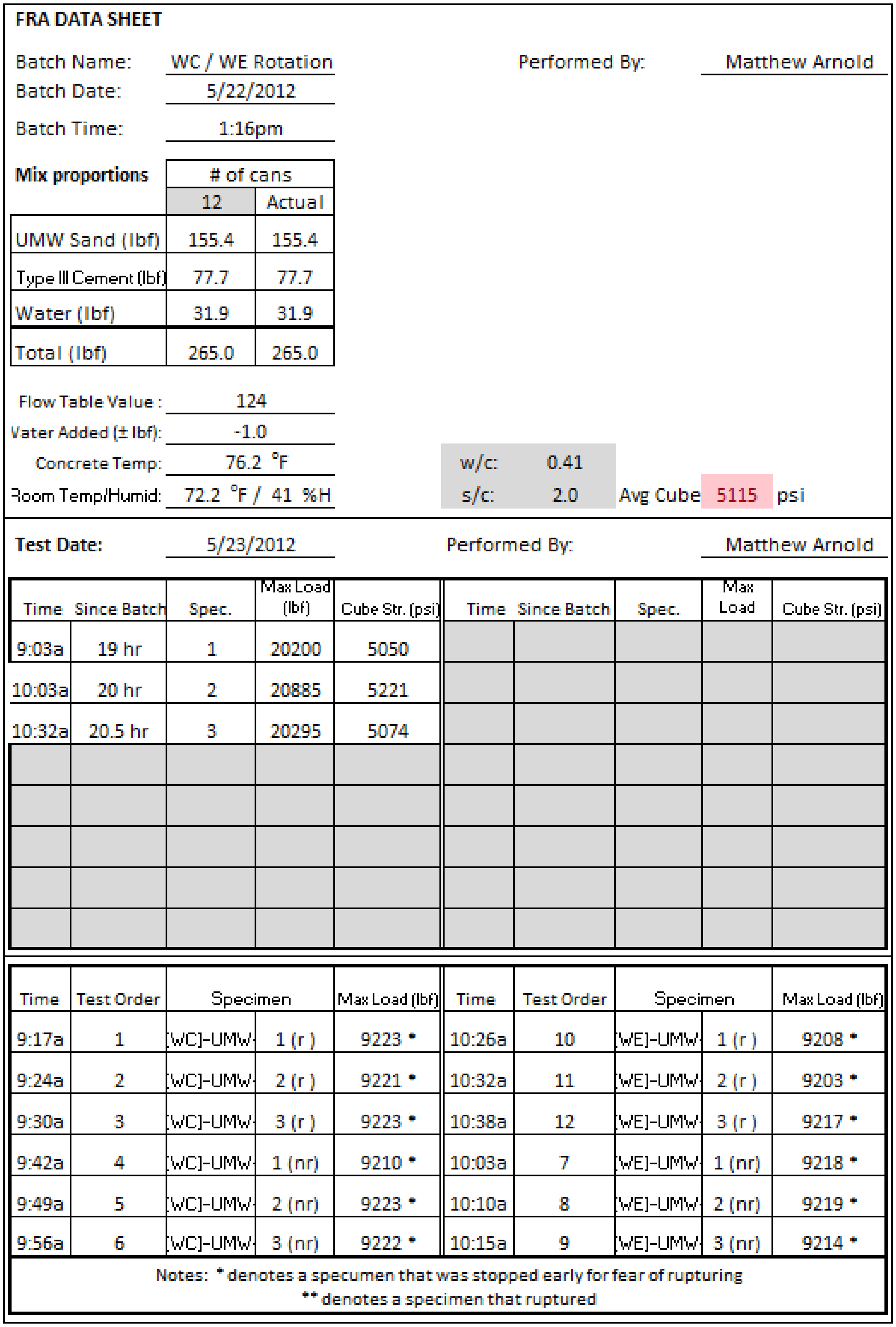
Avg Cube 4765 psi

Test Date: 1/20/2012
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)
8:32a	18 hr	1.1	17835	4459	10:29a		1.10	19930	4983
8:32a		1.2	18030	4508	10:33a		1.11	20005	5001
9:17a	19 hr	1.3	18220	4555	10:48a	20.5 hr	1.12	19660	4915
9:28a		1.4	18760	4690			1.13		
9:35a		1.5	19390	4848			1.14		
9:48a	19.5 hr	1.6	19390	4848			1.15		
9:52a		1.7	18905	4726			1.16		
10:09a	20 hr	1.8	18995	4749			1.17		
10:20a		1.9	19620	4905			1.18		

Time	Since Batch	Specimen Force Control		Max Load (lbf)	Time	Since Batch	Specimen Displ. Control		Max Load (lbf)
8:54a	18.5 hr	[WI]	F-1	8741	9:07a	19 hr	[WI]	D-1	9032
9:14a	19 hr	[WI]	F-2	9279	9:25a		[WI]	D-2	8717
9:34a		[WI]	F-3	9109	9:43a	19.5 hr	[WI]	D-3	8965
9:52a	19.5 hr	[WI]	F-4	8783	9:59a		[WI]	D-4	7248
10:19a	20 hr	[WI]	F-5	7999	10:06a	20 hr	[WI]	D-5	8937
10:26a		[WI]	F-6	9356	10:32a	20.5 hr	[WI]	D-6	8932

Figure A.1 Force control vs. displacement control batch summary



FRA DATA SHEET

Batch Name: WC / WE Rotation
Performed By: Matthew Arnold
Batch Date: 5/22/2012
Batch Time: 1:16pm

Mix proportions	# of cans	
	12	Actual
UMW Sand (lbf)	155.4	155.4
Type III Cement (lbf)	77.7	77.7
Water (lbf)	31.9	31.9
Total (lbf)	265.0	265.0

Flow Table Value : 124
Vater Added (± lbf): -1.0
Concrete Temp: 76.2 °F
Room Temp/Humid: 72.2 °F / 41 %H

w/c: 0.41
s/c: 2.0
Avg Cube 5115 psi

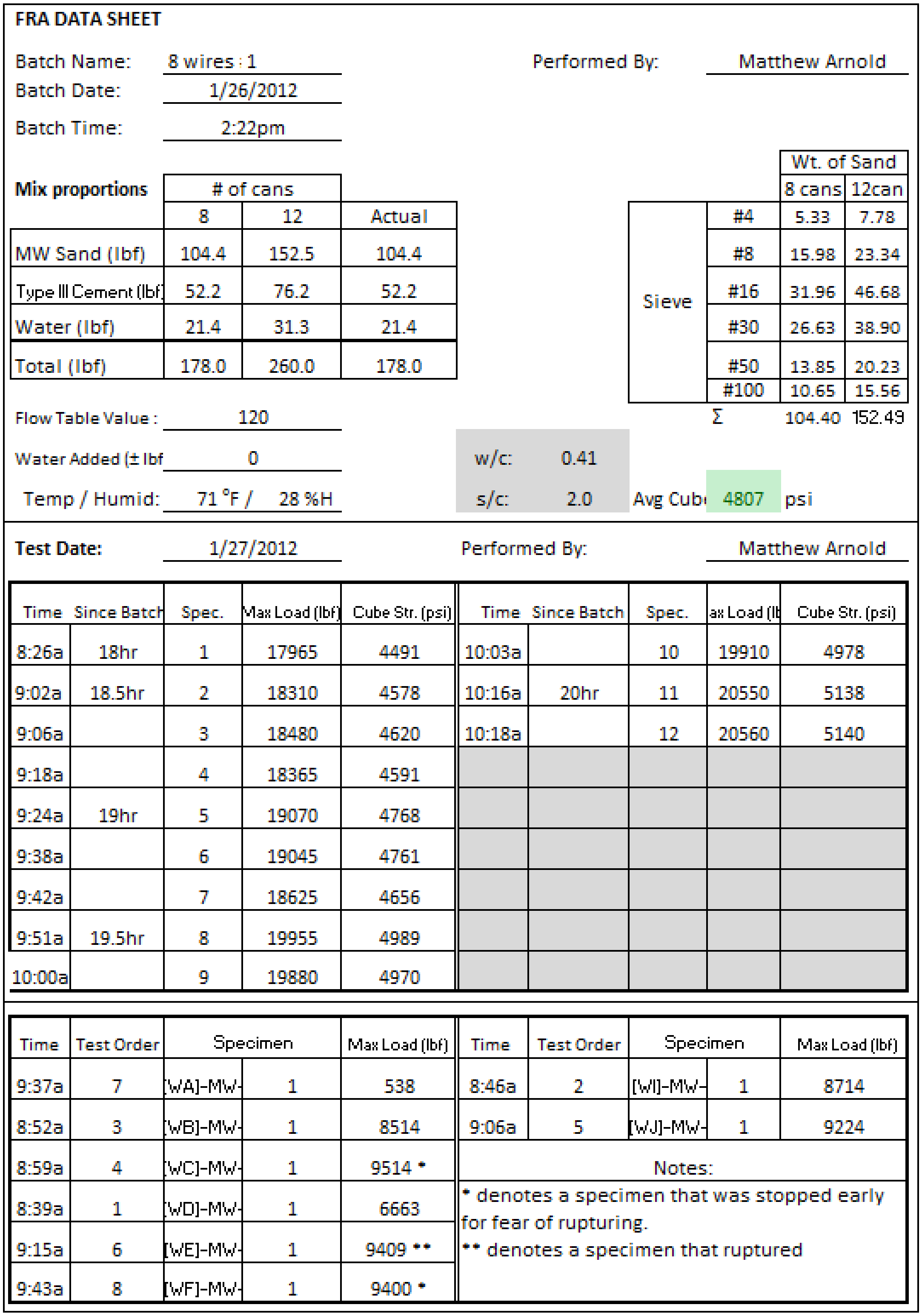
Test Date: 5/23/2012
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
9:03a	19 hr	1	20200	5050					
10:03a	20 hr	2	20885	5221					
10:32a	20.5 hr	3	20295	5074					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:17a	1	[WC]-UMW-	1 (r)	9223 *	10:26a	10	[WE]-UMW-	1 (r)	9208 *
9:24a	2	[WC]-UMW-	2 (r)	9221 *	10:32a	11	[WE]-UMW-	2 (r)	9203 *
9:30a	3	[WC]-UMW-	3 (r)	9223 *	10:38a	12	[WE]-UMW-	3 (r)	9217 *
9:42a	4	[WC]-UMW-	1 (nr)	9210 *	10:03a	7	[WE]-UMW-	1 (nr)	9218 *
9:49a	5	[WC]-UMW-	2 (nr)	9223 *	10:10a	8	[WE]-UMW-	2 (nr)	9219 *
9:56a	6	[WC]-UMW-	3 (nr)	9222 *	10:15a	9	[WE]-UMW-	3 (nr)	9214 *

Notes: * denotes a specumen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure A.2 Rotation allowed vs. rotation restrained batch summary



FRA DATA SHEET

Batch Name: 8 wires : 1

Performed By: Matthew Arnold

Batch Date: 1/26/2012

Batch Time: 2:22pm

Mix proportions	# of cans		
	8	12	Actual
MW Sand (lbf)	104.4	152.5	104.4
Type III Cement (lbf)	52.2	76.2	52.2
Water (lbf)	21.4	31.3	21.4
Total (lbf)	178.0	260.0	178.0

		Wt. of Sand	
		8 cans	12can
Sieve	#4	5.33	7.78
	#8	15.98	23.34
	#16	31.96	46.68
	#30	26.63	38.90
	#50	13.85	20.23
	#100	10.65	15.56
	Σ	104.40	152.49

Flow Table Value : 120

Water Added (± lbf 0

Temp / Humid: 71 °F / 28 %H

w/c: 0.41

s/c: 2.0

Avg Cub 4807 psi

Test Date: 1/27/2012

Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	ax Load (lb	Cube Str. (psi)
8:26a	18hr	1	17965	4491	10:03a		10	19910	4978
9:02a	18.5hr	2	18310	4578	10:16a	20hr	11	20550	5138
9:06a		3	18480	4620	10:18a		12	20560	5140
9:18a		4	18365	4591					
9:24a	19hr	5	19070	4768					
9:38a		6	19045	4761					
9:42a		7	18625	4656					
9:51a	19.5hr	8	19955	4989					
10:00a		9	19880	4970					

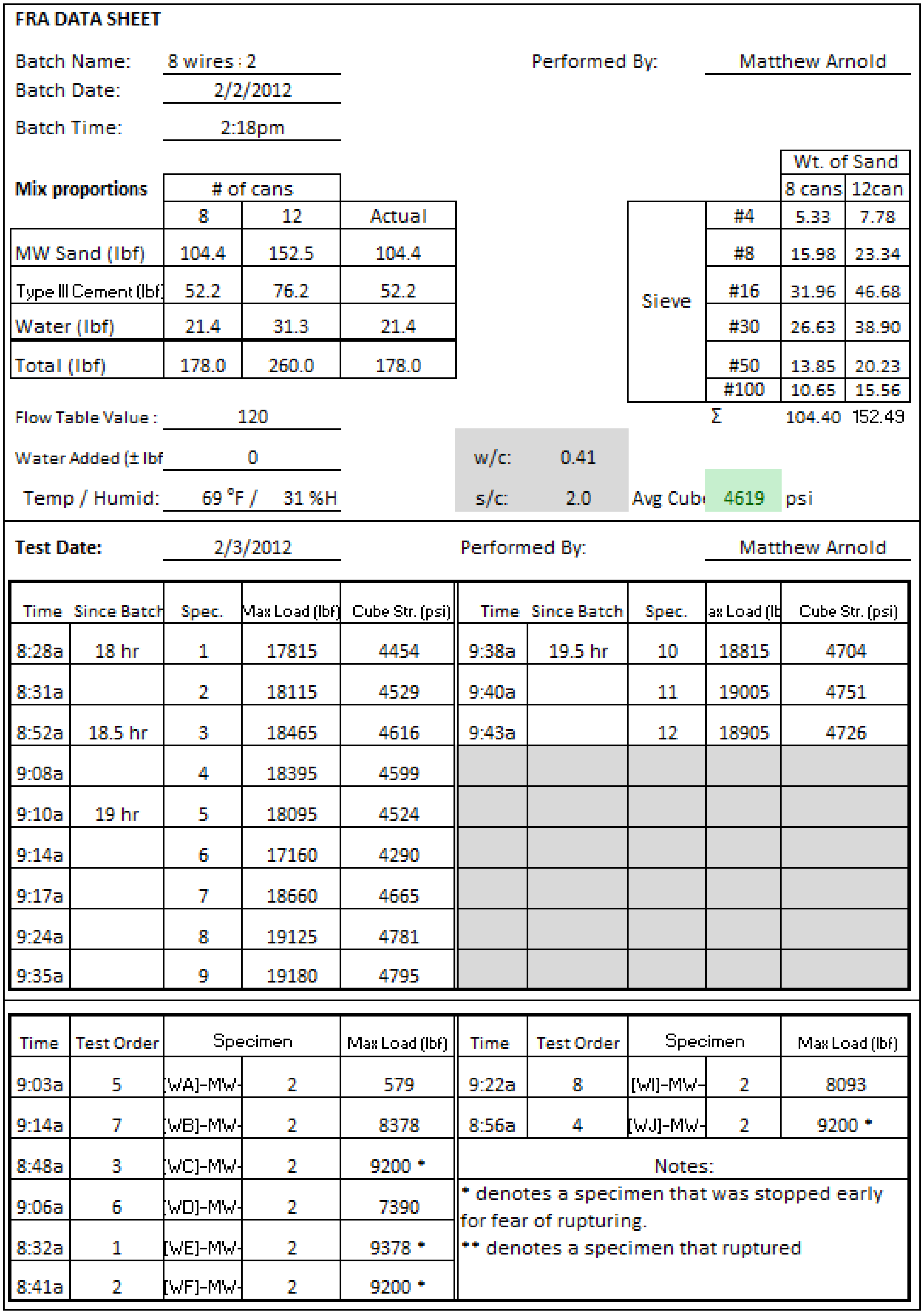
Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:37a	7	[WA]-MW-	1	538	8:46a	2	[WI]-MW-	1	8714
8:52a	3	[WB]-MW-	1	8514	9:06a	5	[WJ]-MW-	1	9224
8:59a	4	[WC]-MW-	1	9514 *					
8:39a	1	[WD]-MW-	1	6663					
9:15a	6	[WE]-MW-	1	9409 **					
9:43a	8	[WF]-MW-	1	9400 *					

Notes:

* denotes a specimen that was stopped early for fear of rupturing.

** denotes a specimen that ruptured

Figure A.3 As-received wires, eight wires #1 batch summary (Midwest sand)



FRA DATA SHEET

Batch Name: 8 wires : 2 Performed By: Matthew Arnold
Batch Date: 2/2/2012
Batch Time: 2:18pm

Mix proportions	# of cans		
	8	12	Actual
MW Sand (lbf)	104.4	152.5	104.4
Type III Cement (lbf	52.2	76.2	52.2
Water (lbf)	21.4	31.3	21.4
Total (lbf)	178.0	260.0	178.0

		Wt. of Sand	
		8 cans	12can
Sieve	#4	5.33	7.78
	#8	15.98	23.34
	#16	31.96	46.68
	#30	26.63	38.90
	#50	13.85	20.23
	#100	10.65	15.56
	Σ	104.40	152.49

Flow Table Value : 120
Water Added (± lbf 0
Temp / Humid: 69 °F / 31 %H
w/c: 0.41
s/c: 2.0
Avg Cub 4619 psi

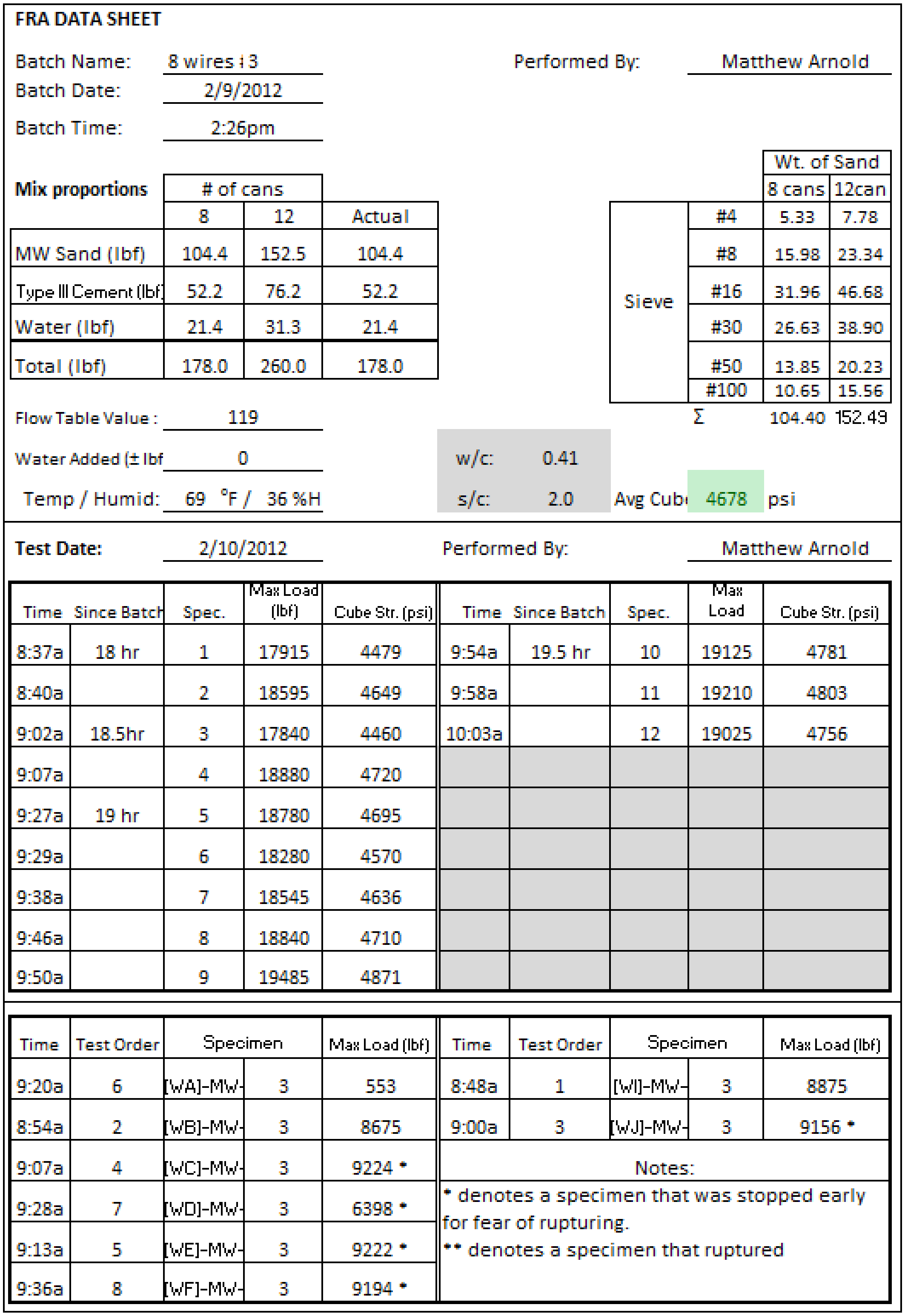
Test Date: 2/3/2012 Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	ax Load (lb	Cube Str. (psi)
8:28a	18 hr	1	17815	4454	9:38a	19.5 hr	10	18815	4704
8:31a		2	18115	4529	9:40a		11	19005	4751
8:52a	18.5 hr	3	18465	4616	9:43a		12	18905	4726
9:08a		4	18395	4599					
9:10a	19 hr	5	18095	4524					
9:14a		6	17160	4290					
9:17a		7	18660	4665					
9:24a		8	19125	4781					
9:35a		9	19180	4795					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:03a	5	[WA]-MW-	2	579	9:22a	8	[WI]-MW-	2	8093
9:14a	7	[WB]-MW-	2	8378	8:56a	4	[WJ]-MW-	2	9200 *
8:48a	3	[WC]-MW-	2	9200 *					
9:06a	6	[WD]-MW-	2	7390					
8:32a	1	[WE]-MW-	2	9378 *					
8:41a	2	[WF]-MW-	2	9200 *					

Notes:
* denotes a specimen that was stopped early for fear of rupturing.
** denotes a specimen that ruptured

Figure A.4 As-received wires, eight wires #2 batch summary (Midwest sand)



FRA DATA SHEET

Batch Name: 8 wires ¡3
Performed By: Matthew Arnold
Batch Date: 2/9/2012
Batch Time: 2:26pm

Mix proportions	# of cans		
	8	12	Actual
MW Sand (lbf)	104.4	152.5	104.4
Type III Cement (lbf)	52.2	76.2	52.2
Water (lbf)	21.4	31.3	21.4
Total (lbf)	178.0	260.0	178.0

		Wt. of Sand	
		8 cans	12can
Sieve	#4	5.33	7.78
	#8	15.98	23.34
	#16	31.96	46.68
	#30	26.63	38.90
	#50	13.85	20.23
	#100	10.65	15.56
	Σ	104.40	152.49

Flow Table Value : 119
Water Added (± lbf 0
Temp / Humid: 69 °F / 36 %H
w/c: 0.41
s/c: 2.0
Avg Cub 4678 psi

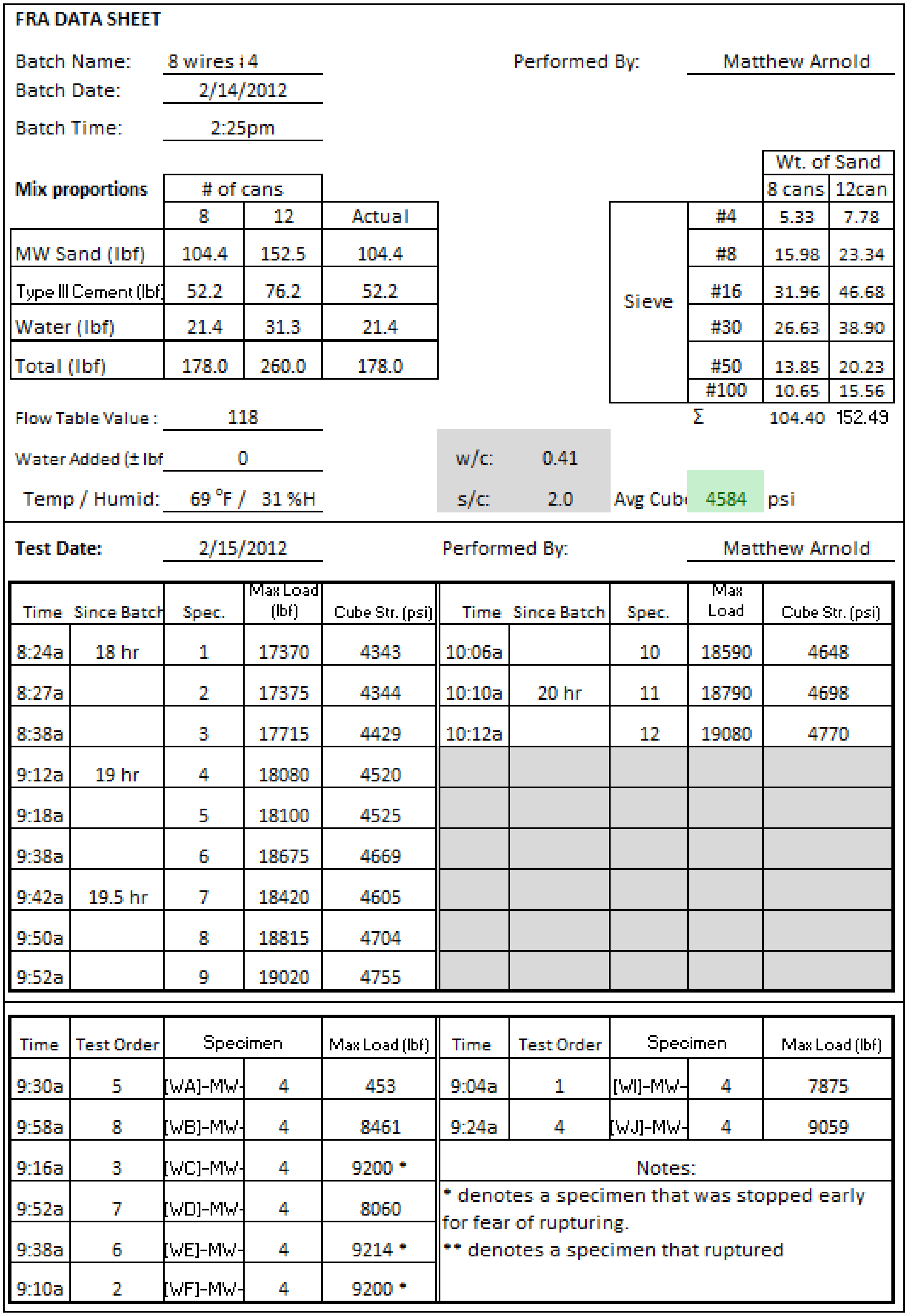
Test Date: 2/10/2012
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:37a	18 hr	1	17915	4479	9:54a	19.5 hr	10	19125	4781
8:40a		2	18595	4649	9:58a		11	19210	4803
9:02a	18.5hr	3	17840	4460	10:03a		12	19025	4756
9:07a		4	18880	4720					
9:27a	19 hr	5	18780	4695					
9:29a		6	18280	4570					
9:38a		7	18545	4636					
9:46a		8	18840	4710					
9:50a		9	19485	4871					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:20a	6	[WA]-MW-	3	553	8:48a	1	[WI]-MW-	3	8875
8:54a	2	[WB]-MW-	3	8675	9:00a	3	[WJ]-MW-	3	9156 *
9:07a	4	[WC]-MW-	3	9224 *					
9:28a	7	[WD]-MW-	3	6398 *					
9:13a	5	[WE]-MW-	3	9222 *					
9:36a	8	[WF]-MW-	3	9194 *					

Notes:
* denotes a specimen that was stopped early for fear of rupturing.
** denotes a specimen that ruptured

Figure A.5 As-received wires, eight wires #3 batch summary (Midwest sand)



FRA DATA SHEET

Batch Name: 8 wires i 4
Batch Date: 2/14/2012
Batch Time: 2:25pm

Performed By: Matthew Arnold

Mix proportions	# of cans		
	8	12	Actual
MW Sand (lbf)	104.4	152.5	104.4
Type III Cement (lbf)	52.2	76.2	52.2
Water (lbf)	21.4	31.3	21.4
Total (lbf)	178.0	260.0	178.0

		Wt. of Sand	
		8 cans	12can
Sieve	#4	5.33	7.78
	#8	15.98	23.34
	#16	31.96	46.68
	#30	26.63	38.90
	#50	13.85	20.23
	#100	10.65	15.56
	Σ	104.40	152.49

Flow Table Value : 118
Water Added (± lbf 0
Temp / Humid: 69 °F / 31 %H

w/c: 0.41
s/c: 2.0

Avg Cub 4584 psi

Test Date: 2/15/2012

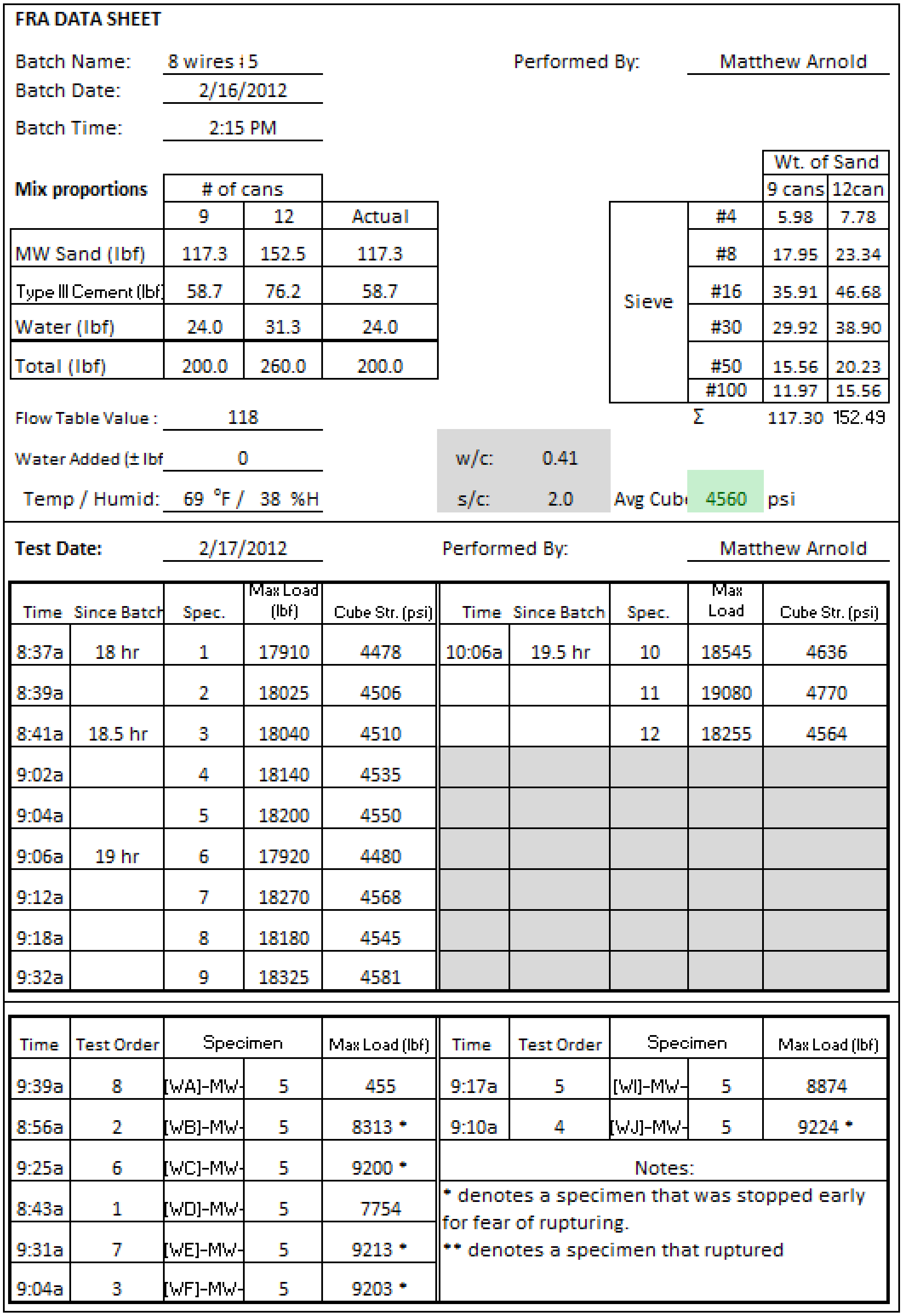
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:24a	18 hr	1	17370	4343	10:06a		10	18590	4648
8:27a		2	17375	4344	10:10a	20 hr	11	18790	4698
8:38a		3	17715	4429	10:12a		12	19080	4770
9:12a	19 hr	4	18080	4520					
9:18a		5	18100	4525					
9:38a		6	18675	4669					
9:42a	19.5 hr	7	18420	4605					
9:50a		8	18815	4704					
9:52a		9	19020	4755					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:30a	5	[WA]-MW-	4	453	9:04a	1	[WI]-MW-	4	7875
9:58a	8	[WB]-MW-	4	8461	9:24a	4	[WJ]-MW-	4	9059
9:16a	3	[WC]-MW-	4	9200 *					
9:52a	7	[WD]-MW-	4	8060					
9:38a	6	[WE]-MW-	4	9214 *					
9:10a	2	[WF]-MW-	4	9200 *					

Notes:
* denotes a specimen that was stopped early for fear of rupturing.
** denotes a specimen that ruptured

Figure A.6 As-received wires, eight wires #4 batch summary (Midwest sand)



FRA DATA SHEET

Batch Name: 8 wires #5

Performed By: Matthew Arnold

Batch Date: 2/16/2012

Batch Time: 2:15 PM

Mix proportions	# of cans		
	9	12	Actual
MW Sand (lbf)	117.3	152.5	117.3
Type III Cement (lbf)	58.7	76.2	58.7
Water (lbf)	24.0	31.3	24.0
Total (lbf)	200.0	260.0	200.0

		Wt. of Sand	
		9 cans	12can
Sieve	#4	5.98	7.78
	#8	17.95	23.34
	#16	35.91	46.68
	#30	29.92	38.90
	#50	15.56	20.23
	#100	11.97	15.56
	Σ	117.30	152.49

Flow Table Value : 118

Water Added (± lbf 0

Temp / Humid: 69 °F / 38 %H

w/c: 0.41

s/c: 2.0

Avg Cub 4560 psi

Test Date: 2/17/2012

Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:37a	18 hr	1	17910	4478	10:06a	19.5 hr	10	18545	4636
8:39a		2	18025	4506			11	19080	4770
8:41a	18.5 hr	3	18040	4510			12	18255	4564
9:02a		4	18140	4535					
9:04a		5	18200	4550					
9:06a	19 hr	6	17920	4480					
9:12a		7	18270	4568					
9:18a		8	18180	4545					
9:32a		9	18325	4581					

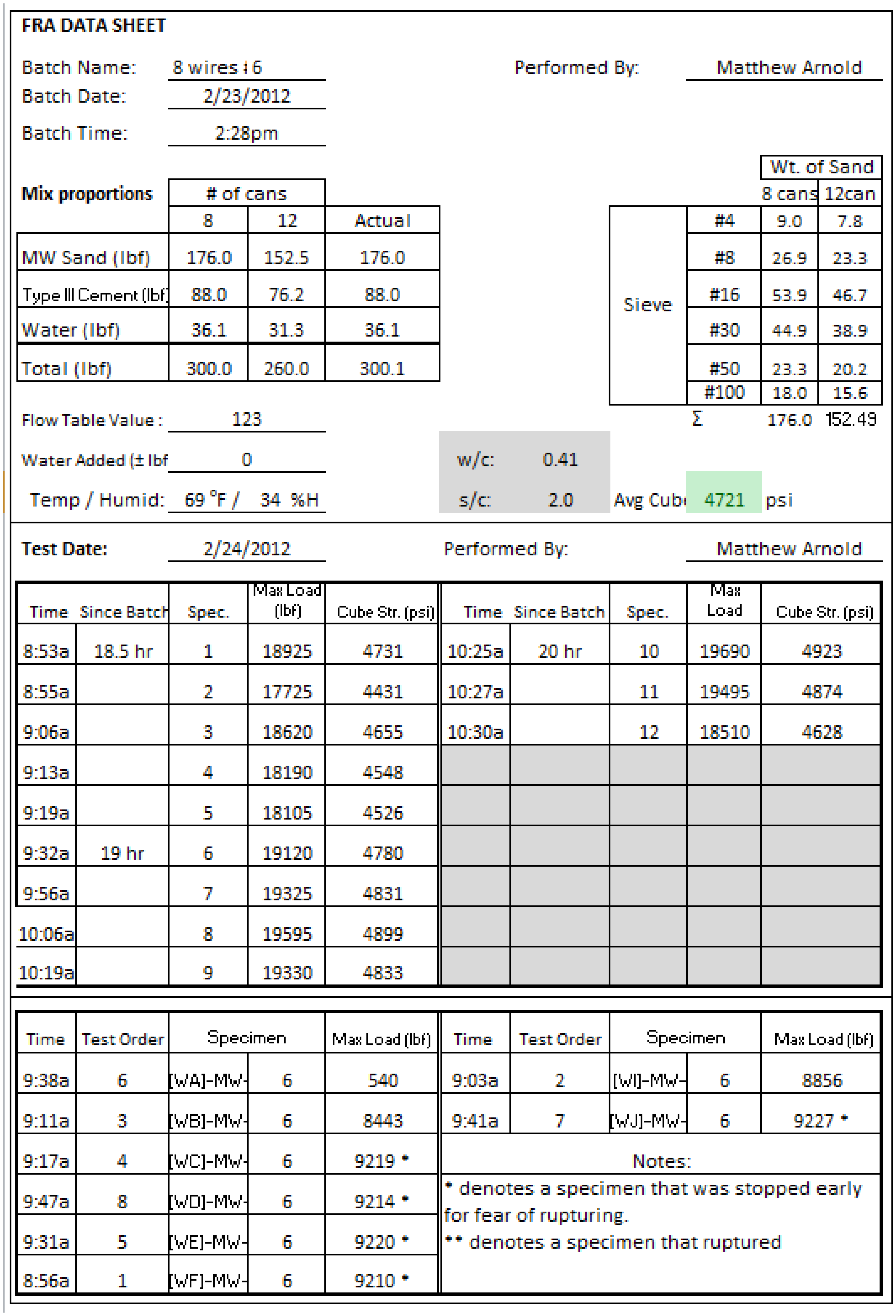
Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:39a	8	[WA]-MW-	5	455	9:17a	5	[WI]-MW-	5	8874
8:56a	2	[WB]-MW-	5	8313 *	9:10a	4	[WJ]-MW-	5	9224 *
9:25a	6	[WC]-MW-	5	9200 *					
8:43a	1	[WD]-MW-	5	7754					
9:31a	7	[WE]-MW-	5	9213 *					
9:04a	3	[WF]-MW-	5	9203 *					

Notes:

* denotes a specimen that was stopped early for fear of rupturing.

** denotes a specimen that ruptured

Figure A.7 As-received wires, eight wires #5 batch summary (Midwest sand)



FRA DATA SHEET

Batch Name: 8 wires i 6
Batch Date: 2/23/2012
Batch Time: 2:28pm
Performed By: Matthew Arnold

Mix proportions	# of cans 8	# of cans 12	Actual
MW Sand (lbf)	176.0	152.5	176.0
Type III Cement (lbf)	88.0	76.2	88.0
Water (lbf)	36.1	31.3	36.1
Total (lbf)	300.0	260.0	300.1

		Wt. of Sand	
		8 cans	12can
Sieve	#4	9.0	7.8
	#8	26.9	23.3
	#16	53.9	46.7
	#30	44.9	38.9
	#50	23.3	20.2
	#100	18.0	15.6
	Σ	176.0	152.49

Flow Table Value : 123
Water Added (± lbf 0
Temp / Humid: 69 °F / 34 %H
w/c: 0.41
s/c: 2.0
Avg Cube 4721 psi

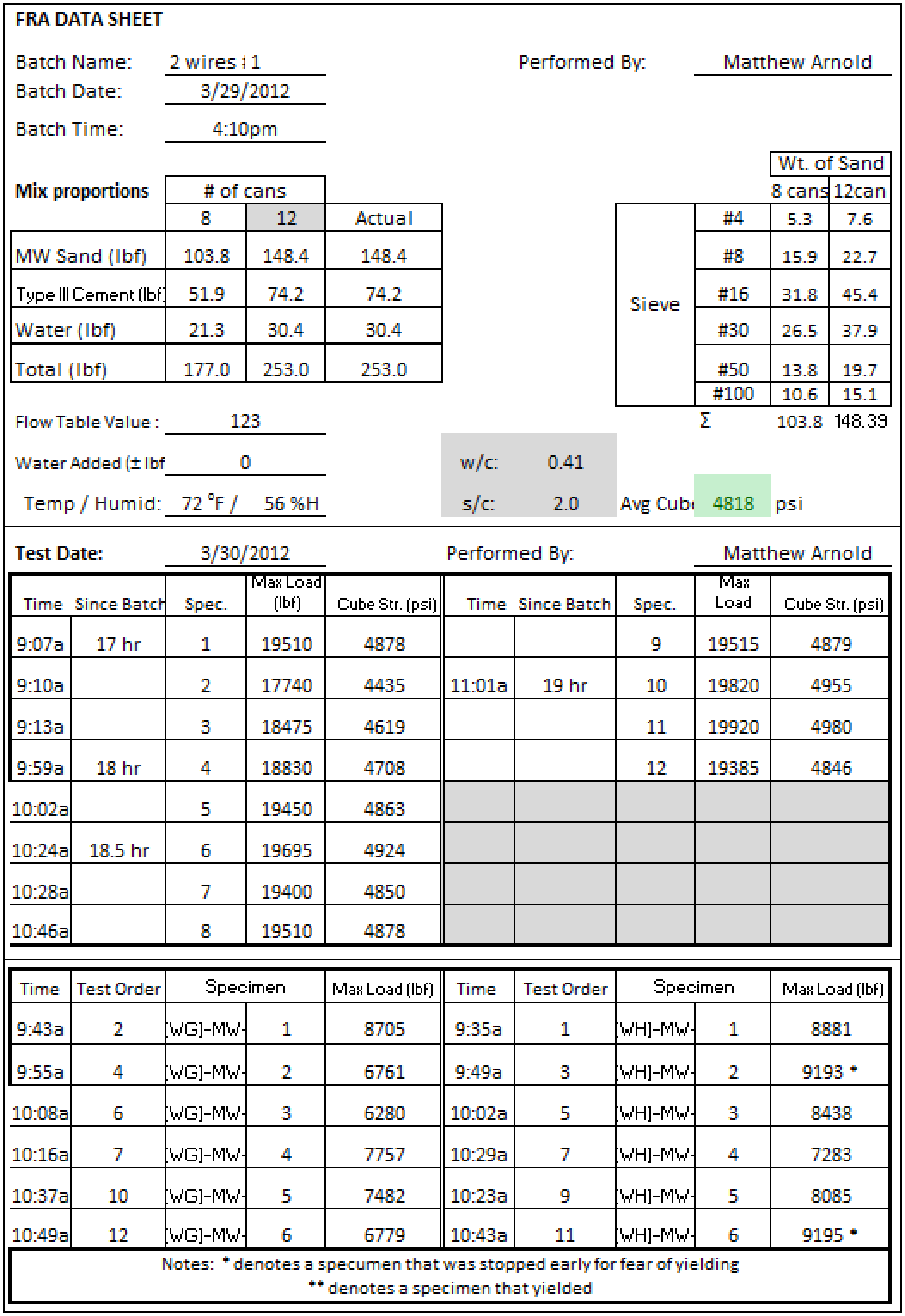
Test Date: 2/24/2012
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:53a	18.5 hr	1	18925	4731	10:25a	20 hr	10	19690	4923
8:55a		2	17725	4431	10:27a		11	19495	4874
9:06a		3	18620	4655	10:30a		12	18510	4628
9:13a		4	18190	4548					
9:19a		5	18105	4526					
9:32a	19 hr	6	19120	4780					
9:56a		7	19325	4831					
10:06a		8	19595	4899					
10:19a		9	19330	4833					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:38a	6	[WA]-MW-	6	540	9:03a	2	[WI]-MW-	6	8856
9:11a	3	[WB]-MW-	6	8443	9:41a	7	[WJ]-MW-	6	9227 *
9:17a	4	[WC]-MW-	6	9219 *					
9:47a	8	[WD]-MW-	6	9214 *					
9:31a	5	[WE]-MW-	6	9220 *					
8:56a	1	[WF]-MW-	6	9210 *					

Notes:
* denotes a specimen that was stopped early for fear of rupturing.
** denotes a specimen that ruptured

Figure A.8 As-received wires, eight wires #6 batch summary (Midwest sand)



FRA DATA SHEET

Batch Name: 2 wires ¦ 1

Performed By: Matthew Arnold

Batch Date: 3/29/2012

Batch Time: 4:10pm

Mix proportions	# of cans		
	8	12	Actual
MW Sand (lbf)	103.8	148.4	148.4
Type III Cement (lbf)	51.9	74.2	74.2
Water (lbf)	21.3	30.4	30.4
Total (lbf)	177.0	253.0	253.0

		Wt. of Sand	
		8 cans	12can
Sieve	#4	5.3	7.6
	#8	15.9	22.7
	#16	31.8	45.4
	#30	26.5	37.9
	#50	13.8	19.7
	#100	10.6	15.1
	Σ	103.8	148.39

Flow Table Value : 123

Water Added (± lbf 0

Temp / Humid: 72 °F / 56 %H

w/c: 0.41

s/c: 2.0

Avg Cub 4818 psi

Test Date: 3/30/2012

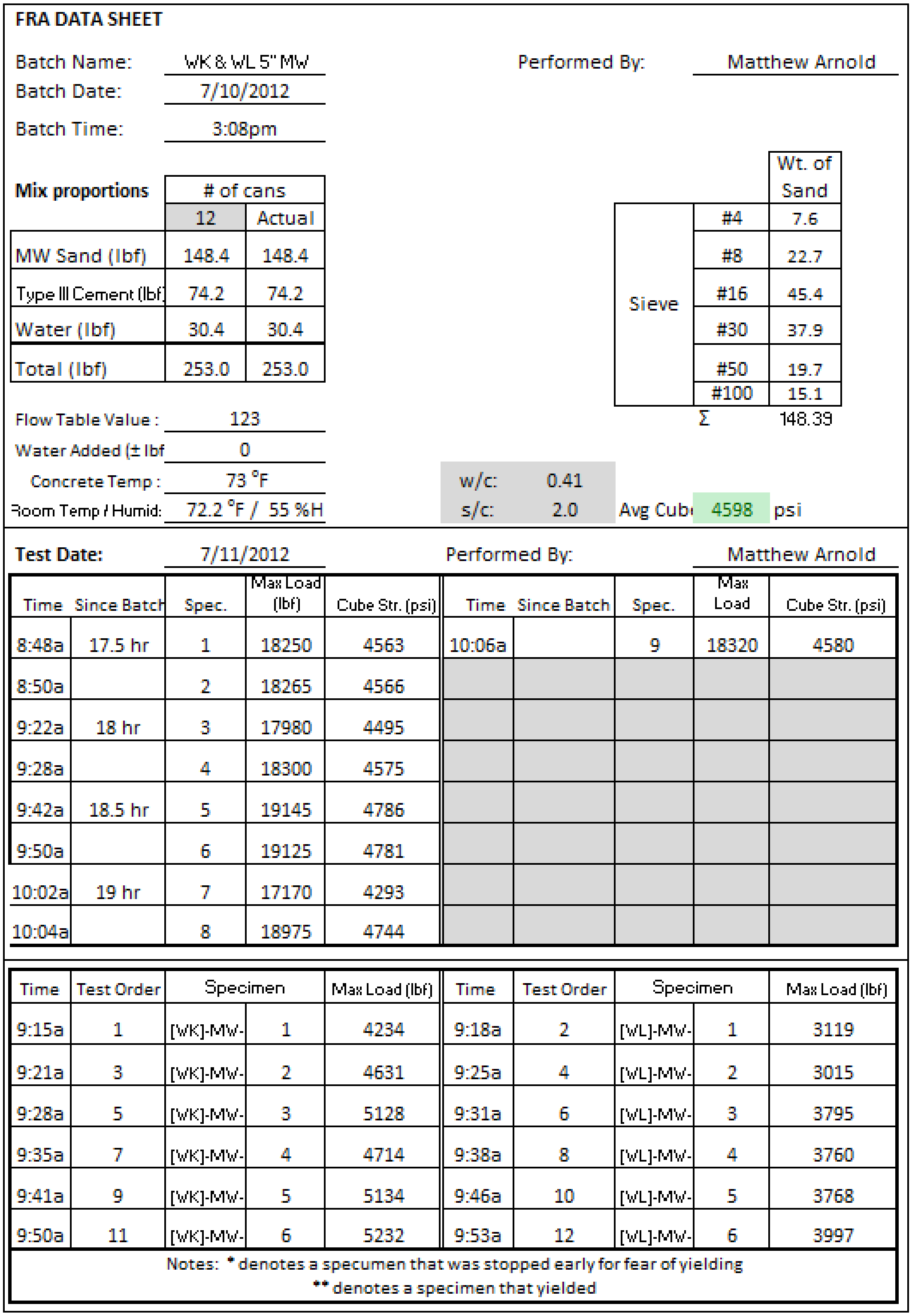
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
9:07a	17 hr	1	19510	4878			9	19515	4879
9:10a		2	17740	4435	11:01a	19 hr	10	19820	4955
9:13a		3	18475	4619			11	19920	4980
9:59a	18 hr	4	18830	4708			12	19385	4846
10:02a		5	19450	4863					
10:24a	18.5 hr	6	19695	4924					
10:28a		7	19400	4850					
10:46a		8	19510	4878					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:43a	2	[WG]-MW-	1	8705	9:35a	1	[WH]-MW-	1	8881
9:55a	4	[WG]-MW-	2	6761	9:49a	3	[WH]-MW-	2	9193 *
10:08a	6	[WG]-MW-	3	6280	10:02a	5	[WH]-MW-	3	8438
10:16a	7	[WG]-MW-	4	7757	10:29a	7	[WH]-MW-	4	7283
10:37a	10	[WG]-MW-	5	7482	10:23a	9	[WH]-MW-	5	8085
10:49a	12	[WG]-MW-	6	6779	10:43a	11	[WH]-MW-	6	9195 *

Notes: * denotes a specumen that was stopped early for fear of yielding
** denotes a specimen that yielded

Figure A.9 As-received wires, [WG] and [WH] batch summary (Midwest sand)



FRA DATA SHEET

Batch Name: WK & WL 5" MW
Performed By: Matthew Arnold
Batch Date: 7/10/2012
Batch Time: 3:08pm

Mix proportions	# of cans	
	12	Actual
MW Sand (lbf)	148.4	148.4
Type III Cement (lbf)	74.2	74.2
Water (lbf)	30.4	30.4
Total (lbf)	253.0	253.0

		Wt. of Sand
Sieve	#4	7.6
	#8	22.7
	#16	45.4
	#30	37.9
	#50	19.7
	#100	15.1
	Σ	148.39

Flow Table Value : 123
Water Added (± lbf: 0
Concrete Temp : 73 °F
Room Temp / Humid: 72.2 °F / 55 %H

w/c: 0.41
s/c: 2.0
Avg Cub 4598 psi

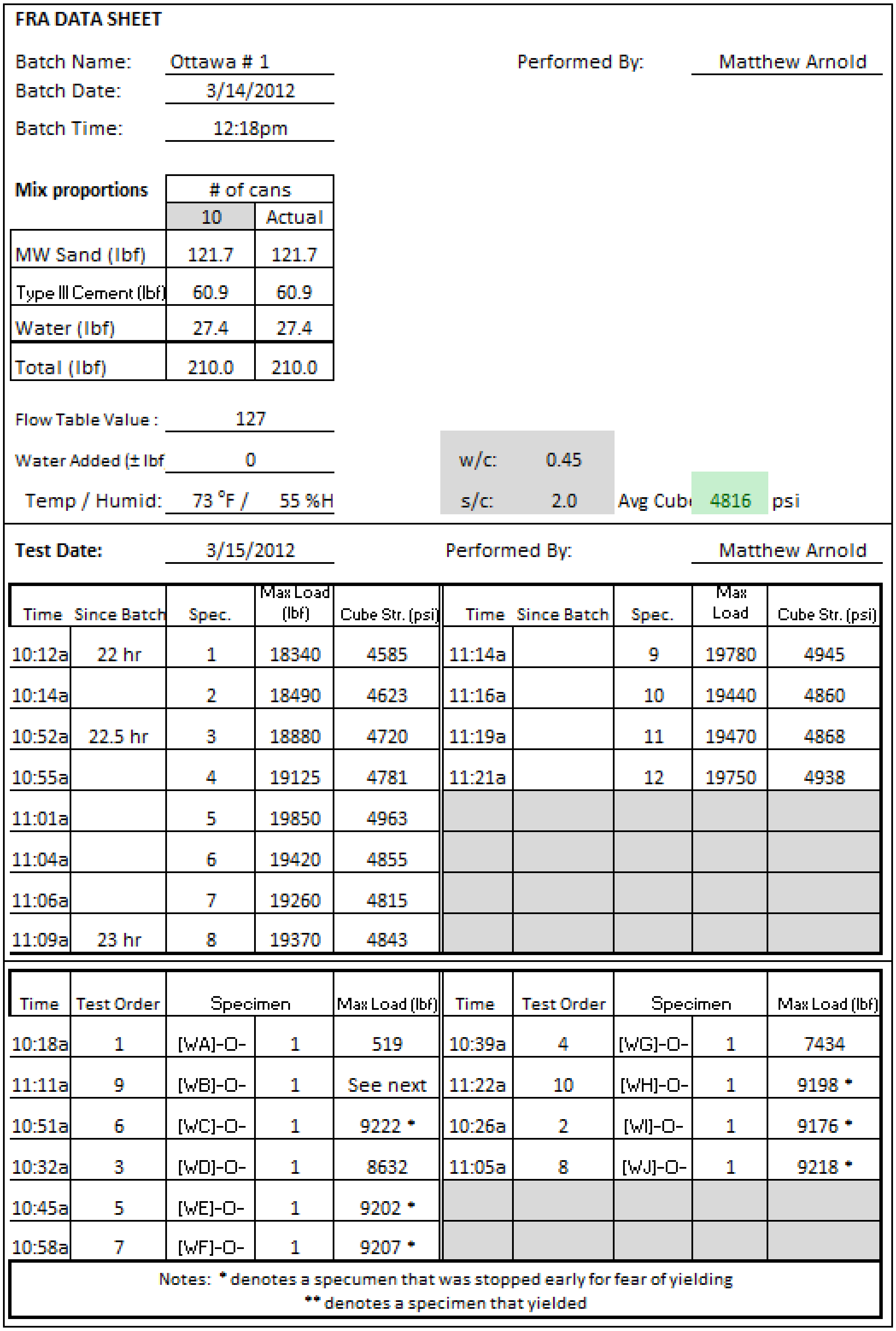
Test Date: 7/11/2012
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:48a	17.5 hr	1	18250	4563	10:06a		9	18320	4580
8:50a		2	18265	4566					
9:22a	18 hr	3	17980	4495					
9:28a		4	18300	4575					
9:42a	18.5 hr	5	19145	4786					
9:50a		6	19125	4781					
10:02a	19 hr	7	17170	4293					
10:04a		8	18975	4744					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:15a	1	[WK]-MW-	1	4234	9:18a	2	[WL]-MW-	1	3119
9:21a	3	[WK]-MW-	2	4631	9:25a	4	[WL]-MW-	2	3015
9:28a	5	[WK]-MW-	3	5128	9:31a	6	[WL]-MW-	3	3795
9:35a	7	[WK]-MW-	4	4714	9:38a	8	[WL]-MW-	4	3760
9:41a	9	[WK]-MW-	5	5134	9:46a	10	[WL]-MW-	5	3768
9:50a	11	[WK]-MW-	6	5232	9:53a	12	[WL]-MW-	6	3997

Notes: * denotes a specumen that was stopped early for fear of yielding
** denotes a specimen that yielded

Figure A.10 As-received wires, [WK] and [WL] batch summary (Midwest sand)



FRA DATA SHEET

Batch Name: Ottawa # 1
Batch Date: 3/14/2012
Batch Time: 12:18pm
Performed By: Matthew Arnold

Mix proportions	# of cans	
	10	Actual
MW Sand (lbf)	121.7	121.7
Type III Cement (lbf)	60.9	60.9
Water (lbf)	27.4	27.4
Total (lbf)	210.0	210.0

Flow Table Value : 127
Water Added (± lbf 0
Temp / Humid: 73 °F / 55 %H
w/c: 0.45
s/c: 2.0
Avg Cub 4816 psi

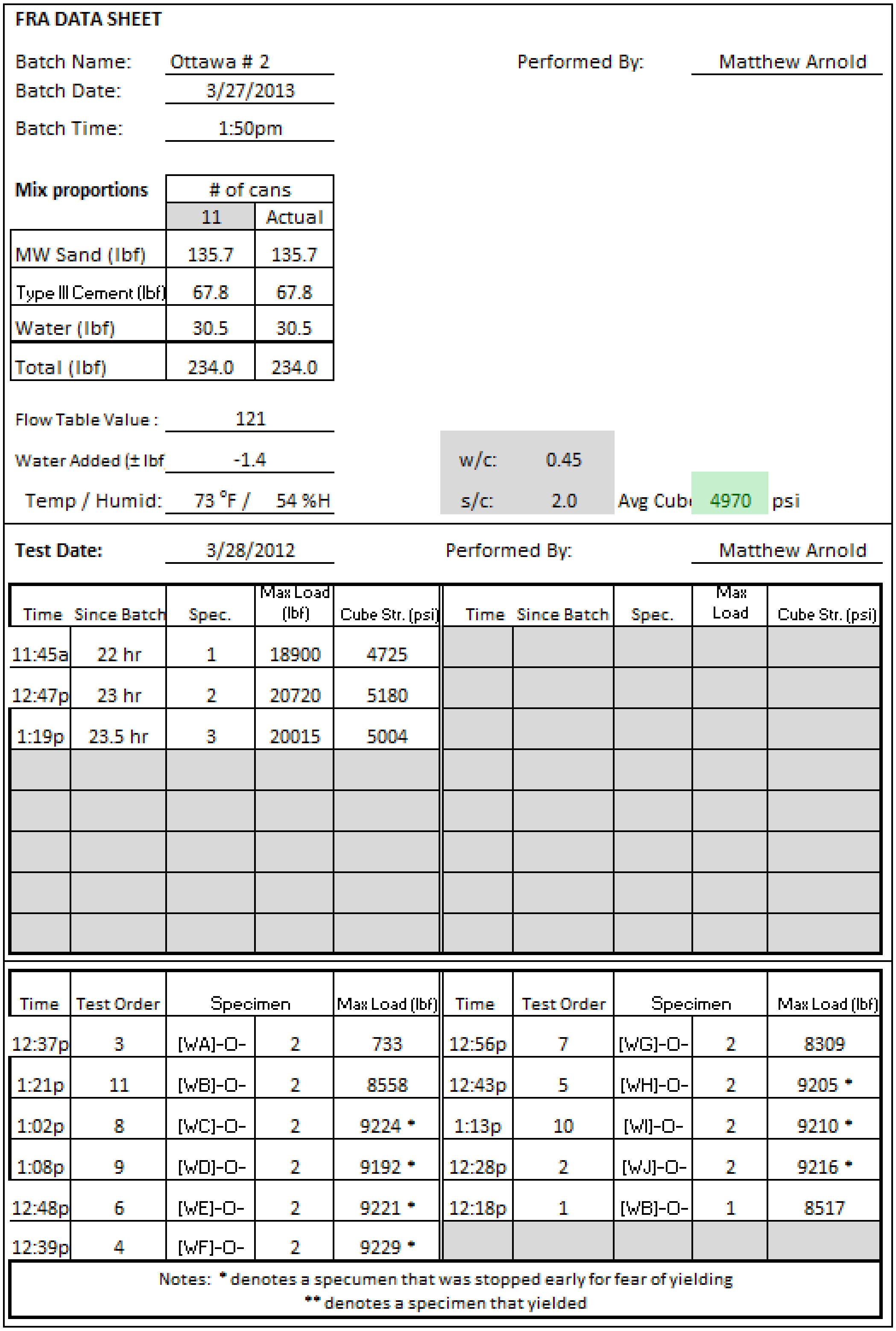
Test Date: 3/15/2012
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
10:12a	22 hr	1	18340	4585	11:14a		9	19780	4945
10:14a		2	18490	4623	11:16a		10	19440	4860
10:52a	22.5 hr	3	18880	4720	11:19a		11	19470	4868
10:55a		4	19125	4781	11:21a		12	19750	4938
11:01a		5	19850	4963					
11:04a		6	19420	4855					
11:06a		7	19260	4815					
11:09a	23 hr	8	19370	4843					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
10:18a	1	[WA]-O-	1	519	10:39a	4	[WG]-O-	1	7434
11:11a	9	[WB]-O-	1	See next	11:22a	10	[WH]-O-	1	9198 *
10:51a	6	[WC]-O-	1	9222 *	10:26a	2	[WI]-O-	1	9176 *
10:32a	3	[WD]-O-	1	8632	11:05a	8	[WJ]-O-	1	9218 *
10:45a	5	[WE]-O-	1	9202 *					
10:58a	7	[WF]-O-	1	9207 *					

Notes: * denotes a specumen that was stopped early for fear of yielding
** denotes a specimen that yielded

Figure A.11 As-received wires, 10 wires #1 batch summary (Ottawa sand)



FRA DATA SHEET

Batch Name: Ottawa # 2
Batch Date: 3/27/2013
Batch Time: 1:50pm
Performed By: Matthew Arnold

Mix proportions	# of cans	
	11	Actual
MW Sand (lbf)	135.7	135.7
Type III Cement (lbf)	67.8	67.8
Water (lbf)	30.5	30.5
Total (lbf)	234.0	234.0

Flow Table Value : 121
Water Added (± lbf -1.4
Temp / Humid: 73 °F / 54 %H

w/c: 0.45
s/c: 2.0
Avg Cub 4970 psi

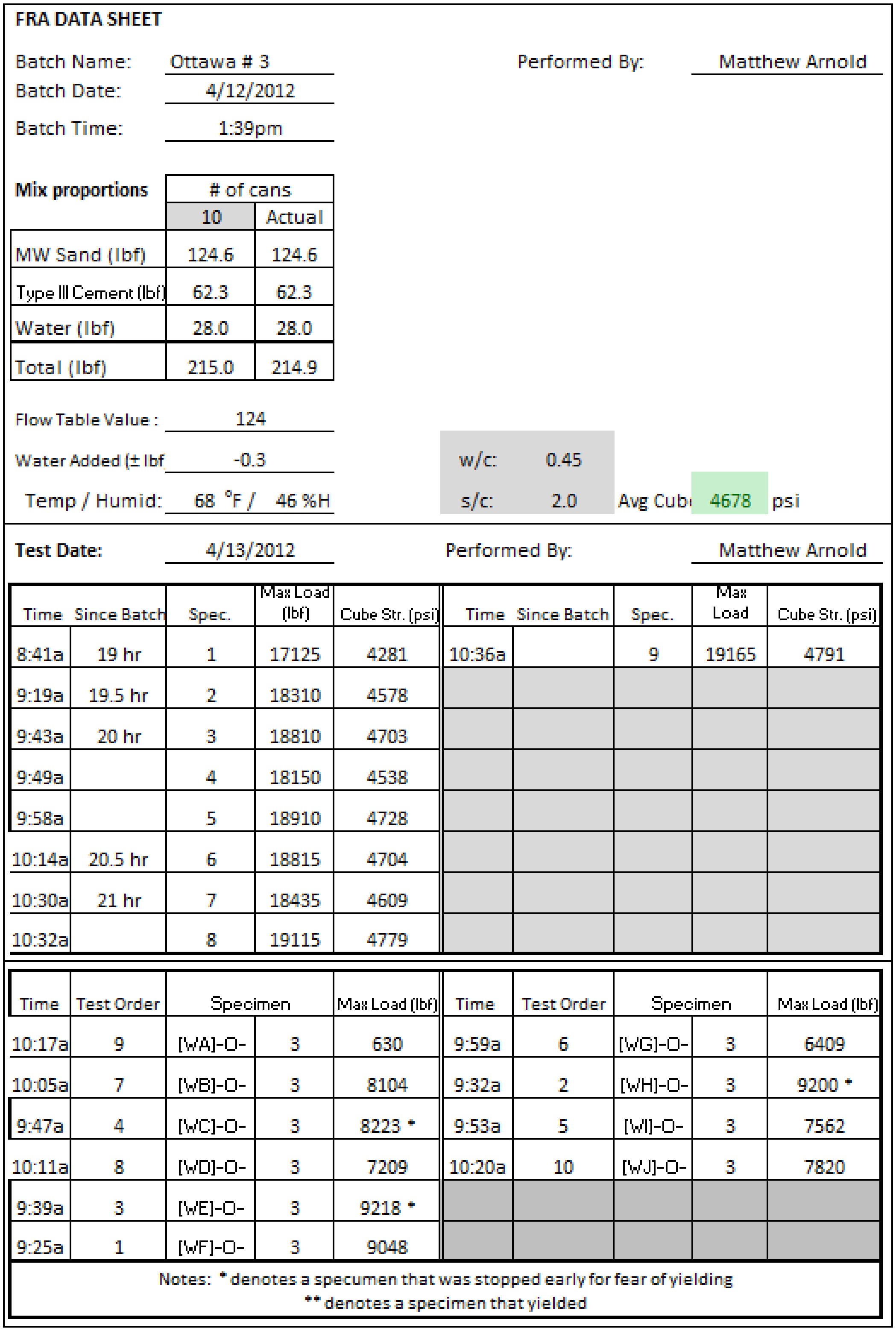
Test Date: 3/28/2012
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
11:45a	22 hr	1	18900	4725					
12:47p	23 hr	2	20720	5180					
1:19p	23.5 hr	3	20015	5004					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
12:37p	3	[WA]-O-	2	733	12:56p	7	[WG]-O-	2	8309
1:21p	11	[WB]-O-	2	8558	12:43p	5	[WH]-O-	2	9205 *
1:02p	8	[WC]-O-	2	9224 *	1:13p	10	[WI]-O-	2	9210 *
1:08p	9	[WD]-O-	2	9192 *	12:28p	2	[WJ]-O-	2	9216 *
12:48p	6	[WE]-O-	2	9221 *	12:18p	1	[WB]-O-	1	8517
12:39p	4	[WF]-O-	2	9229 *					

Notes: * denotes a specumen that was stopped early for fear of yielding
** denotes a specimen that yielded

Figure A.12 As-received wires, 10 wires #2 batch summary (Ottawa sand)



FRA DATA SHEET

Batch Name: Ottawa # 3
Performed By: Matthew Arnold
Batch Date: 4/12/2012
Batch Time: 1:39pm

Mix proportions	# of cans	
	10	Actual
MW Sand (lbf)	124.6	124.6
Type III Cement (lbf)	62.3	62.3
Water (lbf)	28.0	28.0
Total (lbf)	215.0	214.9

Flow Table Value : 124
Water Added (± lbf -0.3
Temp / Humid: 68 °F / 46 %H
w/c: 0.45
s/c: 2.0
Avg Cub 4678 psi

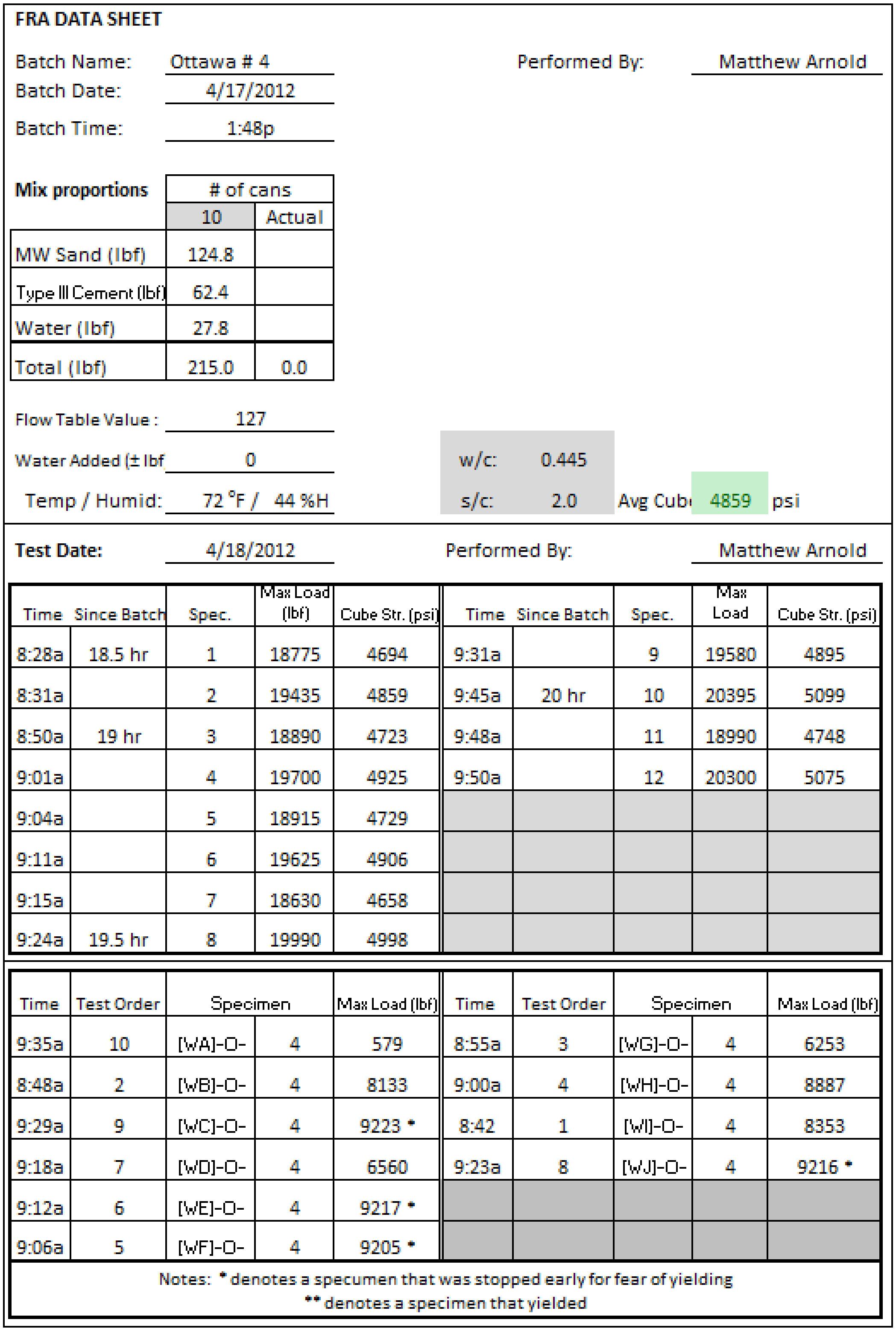
Test Date: 4/13/2012
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:41a	19 hr	1	17125	4281	10:36a		9	19165	4791
9:19a	19.5 hr	2	18310	4578					
9:43a	20 hr	3	18810	4703					
9:49a		4	18150	4538					
9:58a		5	18910	4728					
10:14a	20.5 hr	6	18815	4704					
10:30a	21 hr	7	18435	4609					
10:32a		8	19115	4779					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
10:17a	9	[WA]-O-	3	630	9:59a	6	[WG]-O-	3	6409
10:05a	7	[WB]-O-	3	8104	9:32a	2	[WH]-O-	3	9200 *
9:47a	4	[WC]-O-	3	8223 *	9:53a	5	[WI]-O-	3	7562
10:11a	8	[WD]-O-	3	7209	10:20a	10	[WJ]-O-	3	7820
9:39a	3	[WE]-O-	3	9218 *					
9:25a	1	[WF]-O-	3	9048					

Notes: * denotes a specumen that was stopped early for fear of yielding
** denotes a specimen that yielded

Figure A.13 As-received wires, 10 wires #3 batch summary (Ottawa sand)



FRA DATA SHEET

Batch Name: Ottawa # 4

Performed By: Matthew Arnold

Batch Date: 4/17/2012

Batch Time: 1:48p

Mix proportions	# of cans	
	10	Actual
MW Sand (lbf)	124.8	
Type III Cement (lbf)	62.4	
Water (lbf)	27.8	
Total (lbf)	215.0	0.0

Flow Table Value : 127

Water Added (± lbf 0

Temp / Humid: 72 °F / 44 %H

w/c: 0.445

s/c: 2.0

Avg Cub 4859 psi

Test Date: 4/18/2012

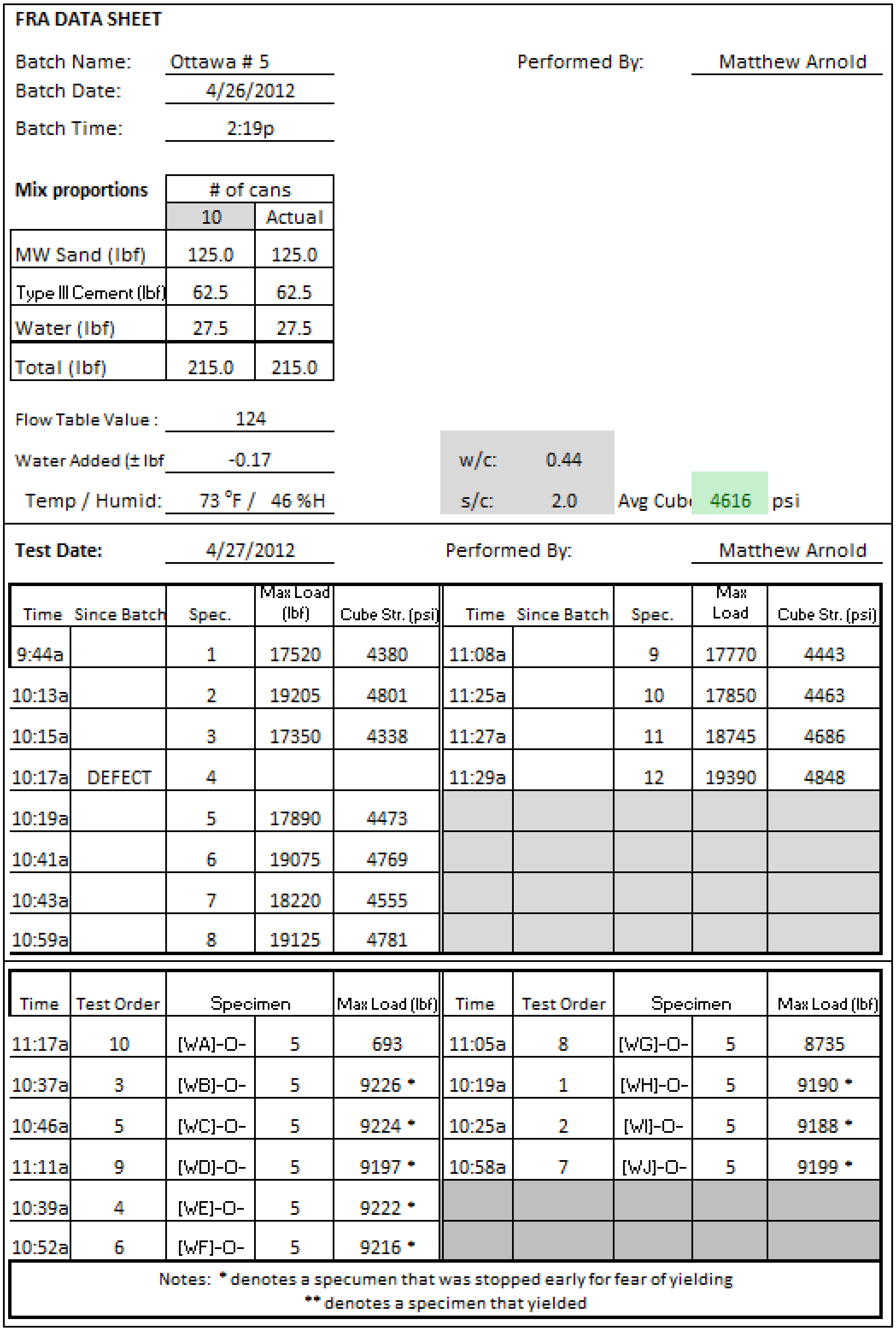
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:28a	18.5 hr	1	18775	4694	9:31a		9	19580	4895
8:31a		2	19435	4859	9:45a	20 hr	10	20395	5099
8:50a	19 hr	3	18890	4723	9:48a		11	18990	4748
9:01a		4	19700	4925	9:50a		12	20300	5075
9:04a		5	18915	4729					
9:11a		6	19625	4906					
9:15a		7	18630	4658					
9:24a	19.5 hr	8	19990	4998					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:35a	10	[WA]-O-	4	579	8:55a	3	[WG]-O-	4	6253
8:48a	2	[WB]-O-	4	8133	9:00a	4	[WH]-O-	4	8887
9:29a	9	[WC]-O-	4	9223 *	8:42	1	[WI]-O-	4	8353
9:18a	7	[WD]-O-	4	6560	9:23a	8	[WJ]-O-	4	9216 *
9:12a	6	[WE]-O-	4	9217 *					
9:06a	5	[WF]-O-	4	9205 *					

Notes: * denotes a specumen that was stopped early for fear of yielding
** denotes a specimen that yielded

Figure A.14 As-received wires, 10 wires #4 batch summary (Ottawa sand)



FRA DATA SHEET

Batch Name: Ottawa # 5
Performed By: Matthew Arnold
Batch Date: 4/26/2012
Batch Time: 2:19p

Mix proportions	# of cans	
	10	Actual
MW Sand (lbf)	125.0	125.0
Type III Cement (lbf)	62.5	62.5
Water (lbf)	27.5	27.5
Total (lbf)	215.0	215.0

Flow Table Value : 124
Water Added (± lbf -0.17
Temp / Humid: 73 °F / 46 %H

w/c: 0.44
s/c: 2.0
Avg Cub 4616 psi

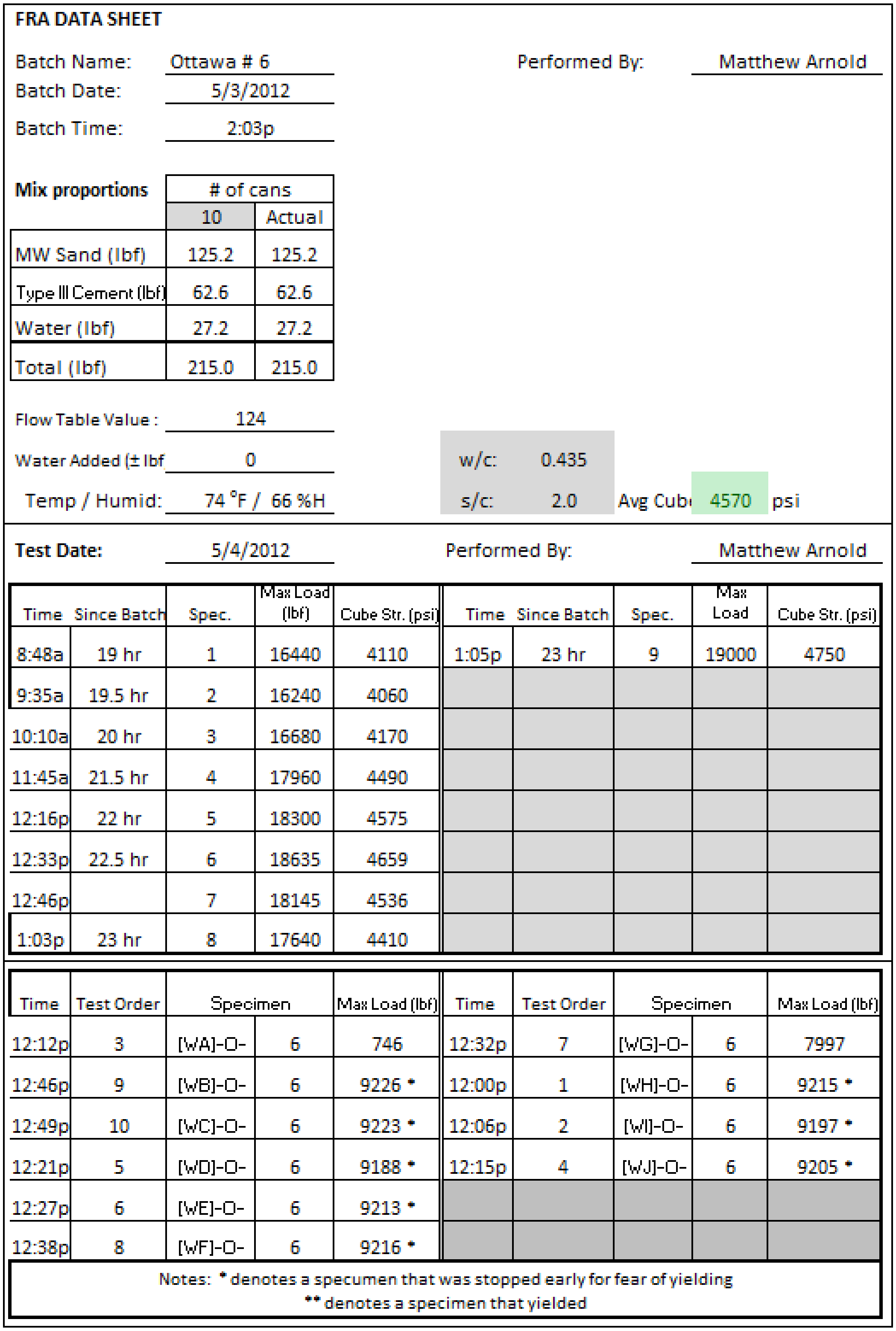
Test Date: 4/27/2012
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
9:44a		1	17520	4380	11:08a		9	17770	4443
10:13a		2	19205	4801	11:25a		10	17850	4463
10:15a		3	17350	4338	11:27a		11	18745	4686
10:17a	DEFECT	4			11:29a		12	19390	4848
10:19a		5	17890	4473					
10:41a		6	19075	4769					
10:43a		7	18220	4555					
10:59a		8	19125	4781					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
11:17a	10	[WA]-O-	5	693	11:05a	8	[WG]-O-	5	8735
10:37a	3	[WB]-O-	5	9226 *	10:19a	1	[WH]-O-	5	9190 *
10:46a	5	[WC]-O-	5	9224 *	10:25a	2	[WI]-O-	5	9188 *
11:11a	9	[WD]-O-	5	9197 *	10:58a	7	[WJ]-O-	5	9199 *
10:39a	4	[WE]-O-	5	9222 *					
10:52a	6	[WF]-O-	5	9216 *					

Notes: * denotes a specumen that was stopped early for fear of yielding
** denotes a specimen that yielded

Figure A.15 As-received wires, 10 wires #5 batch summary (Ottawa sand)



FRA DATA SHEET

Batch Name: Ottawa # 6 Performed By: Matthew Arnold
Batch Date: 5/3/2012
Batch Time: 2:03p

Mix proportions	# of cans	
	10	Actual
MW Sand (lbf)	125.2	125.2
Type III Cement (lbf)	62.6	62.6
Water (lbf)	27.2	27.2
Total (lbf)	215.0	215.0

Flow Table Value : 124
Water Added (± lbf 0 w/c: 0.435
Temp / Humid: 74 °F / 66 %H s/c: 2.0 Avg Cub 4570 psi

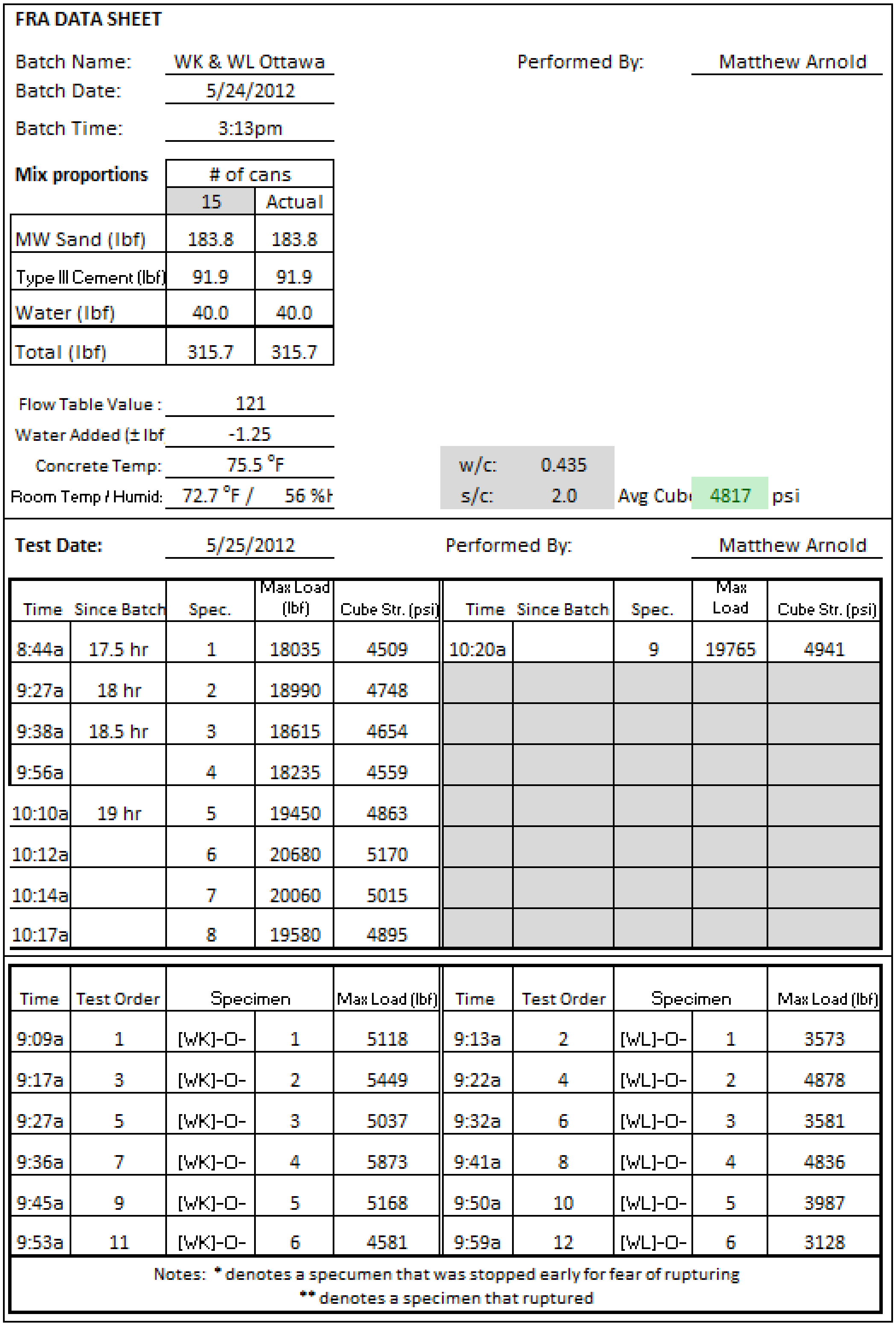
Test Date: 5/4/2012 Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:48a	19 hr	1	16440	4110	1:05p	23 hr	9	19000	4750
9:35a	19.5 hr	2	16240	4060					
10:10a	20 hr	3	16680	4170					
11:45a	21.5 hr	4	17960	4490					
12:16p	22 hr	5	18300	4575					
12:33p	22.5 hr	6	18635	4659					
12:46p		7	18145	4536					
1:03p	23 hr	8	17640	4410					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
12:12p	3	[WA]-O-	6	746	12:32p	7	[WG]-O-	6	7997
12:46p	9	[WB]-O-	6	9226 *	12:00p	1	[WH]-O-	6	9215 *
12:49p	10	[WC]-O-	6	9223 *	12:06p	2	[WI]-O-	6	9197 *
12:21p	5	[WD]-O-	6	9188 *	12:15p	4	[WJ]-O-	6	9205 *
12:27p	6	[WE]-O-	6	9213 *					
12:38p	8	[WF]-O-	6	9216 *					

Notes: * denotes a specumen that was stopped early for fear of yielding
** denotes a specimen that yielded

Figure A.16 As-received wires, 10 wires #6 batch summary (Ottawa sand)



FRA DATA SHEET

Batch Name: WK & WL Ottawa
Performed By: Matthew Arnold
Batch Date: 5/24/2012
Batch Time: 3:13pm

Mix proportions	# of cans	
	15	Actual
MW Sand (lbf)	183.8	183.8
Type III Cement (lbf)	91.9	91.9
Water (lbf)	40.0	40.0
Total (lbf)	315.7	315.7

Flow Table Value : 121
Water Added (± lbf -1.25
Concrete Temp: 75.5 °F
Room Temp / Humid: 72.7 °F / 56 %
w/c: 0.435
s/c: 2.0
Avg Cub 4817 psi

Test Date: 5/25/2012
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:44a	17.5 hr	1	18035	4509	10:20a		9	19765	4941
9:27a	18 hr	2	18990	4748					
9:38a	18.5 hr	3	18615	4654					
9:56a		4	18235	4559					
10:10a	19 hr	5	19450	4863					
10:12a		6	20680	5170					
10:14a		7	20060	5015					
10:17a		8	19580	4895					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:09a	1	[WK]-O-	1	5118	9:13a	2	[WL]-O-	1	3573
9:17a	3	[WK]-O-	2	5449	9:22a	4	[WL]-O-	2	4878
9:27a	5	[WK]-O-	3	5037	9:32a	6	[WL]-O-	3	3581
9:36a	7	[WK]-O-	4	5873	9:41a	8	[WL]-O-	4	4836
9:45a	9	[WK]-O-	5	5168	9:50a	10	[WL]-O-	5	3987
9:53a	11	[WK]-O-	6	4581	9:59a	12	[WL]-O-	6	3128

Notes: * denotes a specumen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure A.17 As-received wires, [WK] and [WL] batch summary (Ottawa sand)

Appendix B - Lab Phase, Wire; Test Development Individual Pullout Graphs

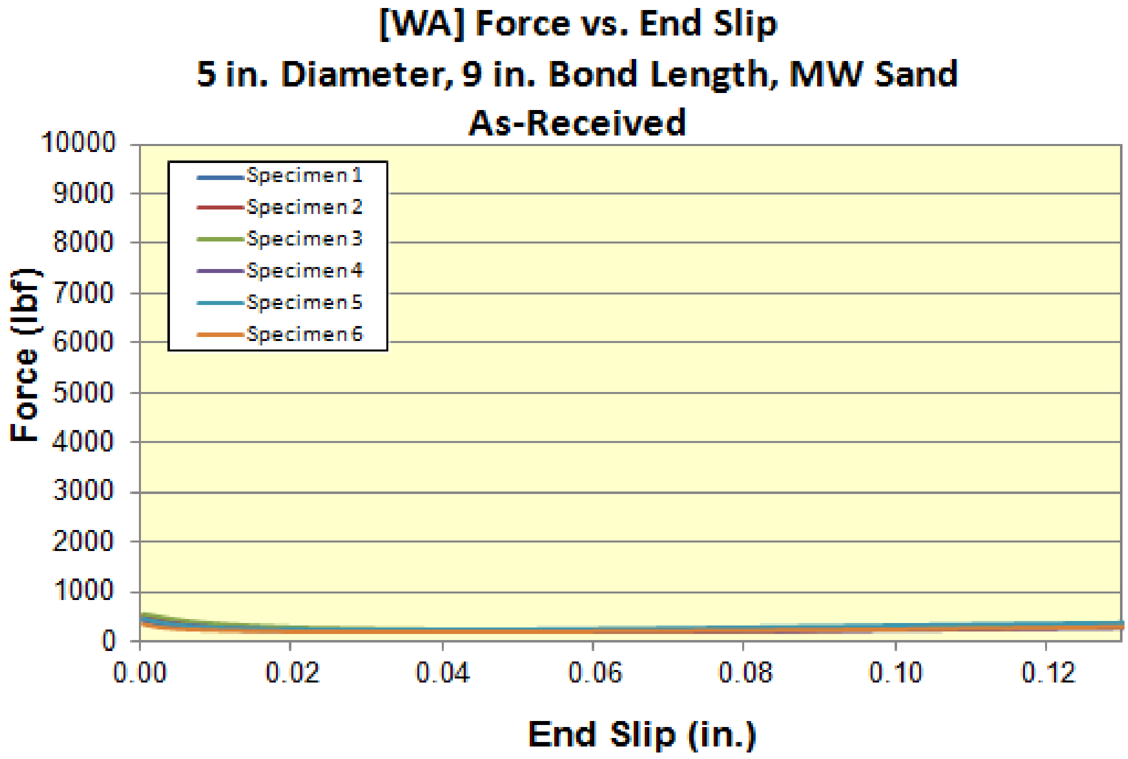


Figure B.1 Midwest sand [WA] force vs. end slip individual graphs

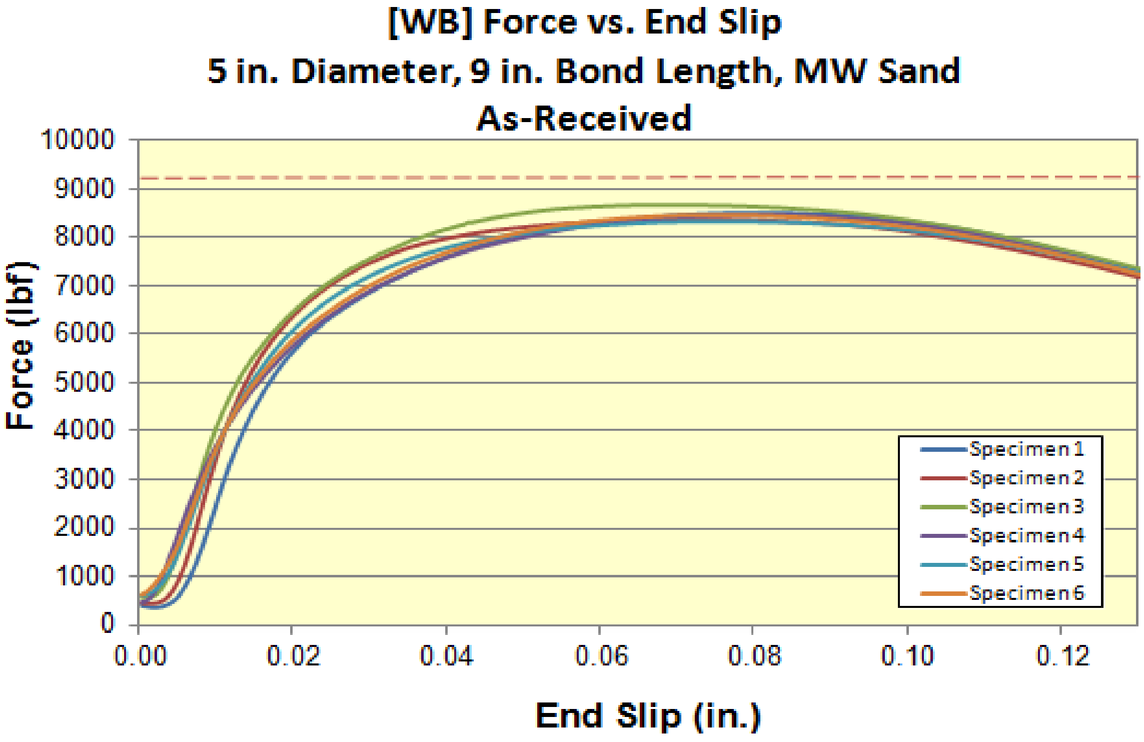


Figure B.2 Midwest sand [WB] force vs. end slip individual graphs

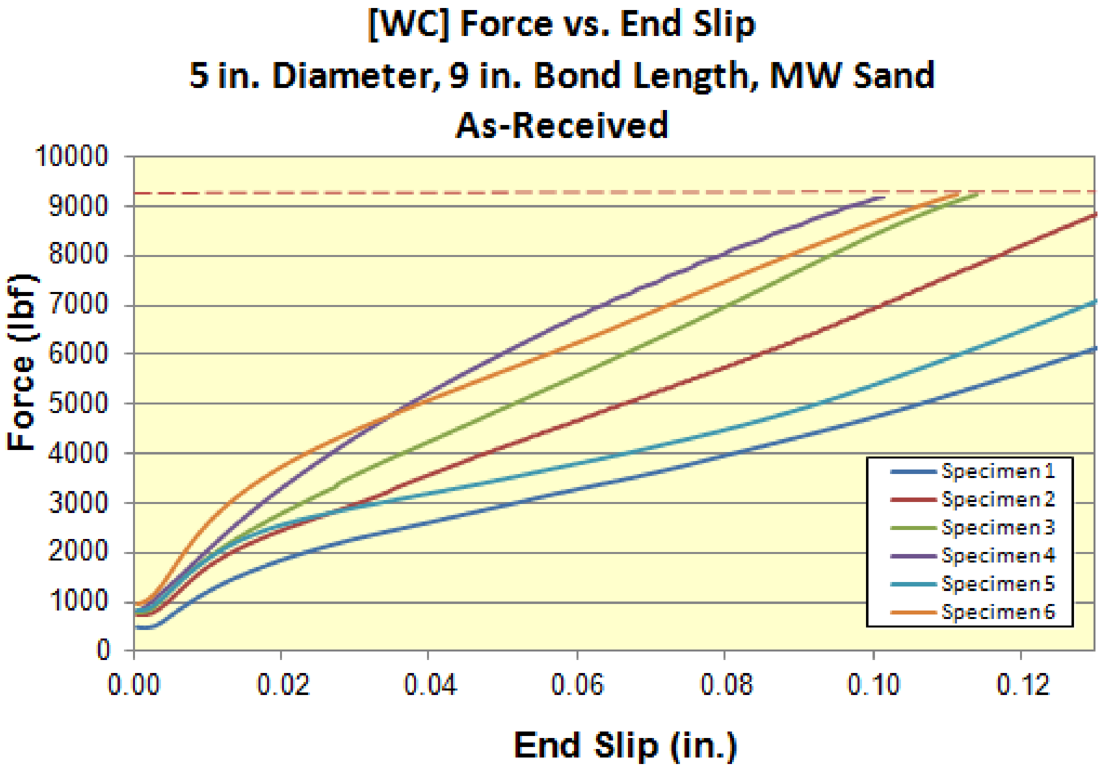


Figure B.3 Midwest sand [WC] force vs. end slip individual graphs

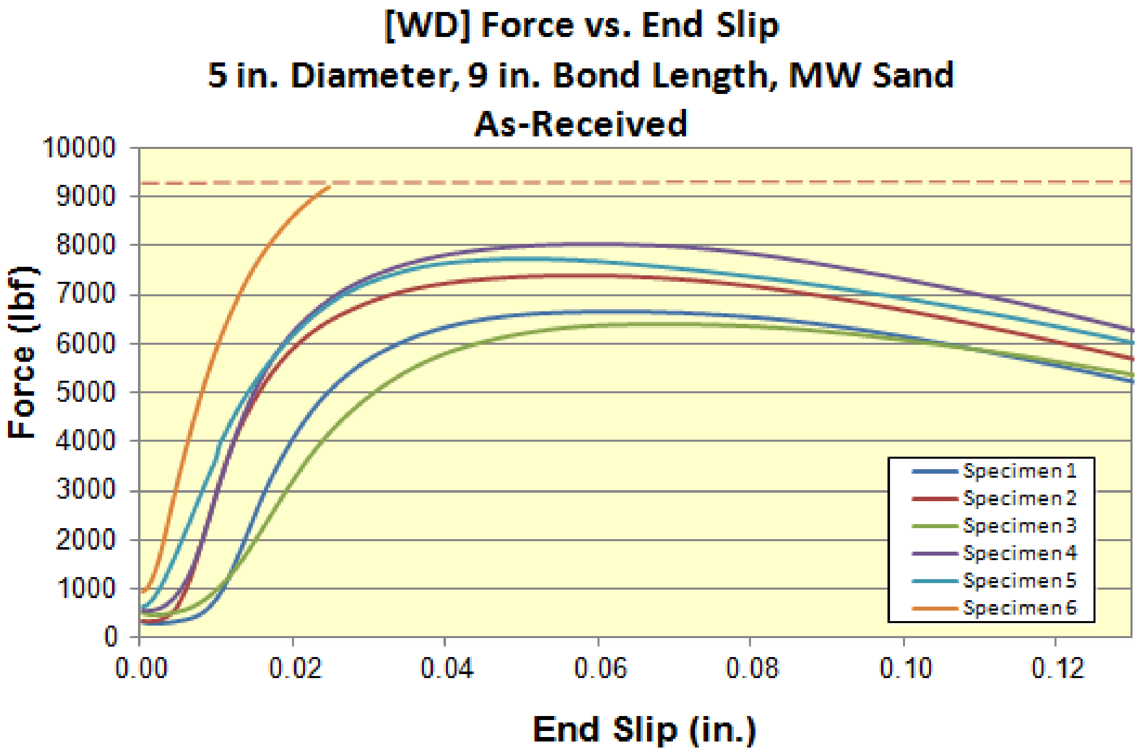


Figure B.4 Midwest sand [WD] force vs. end slip individual graphs

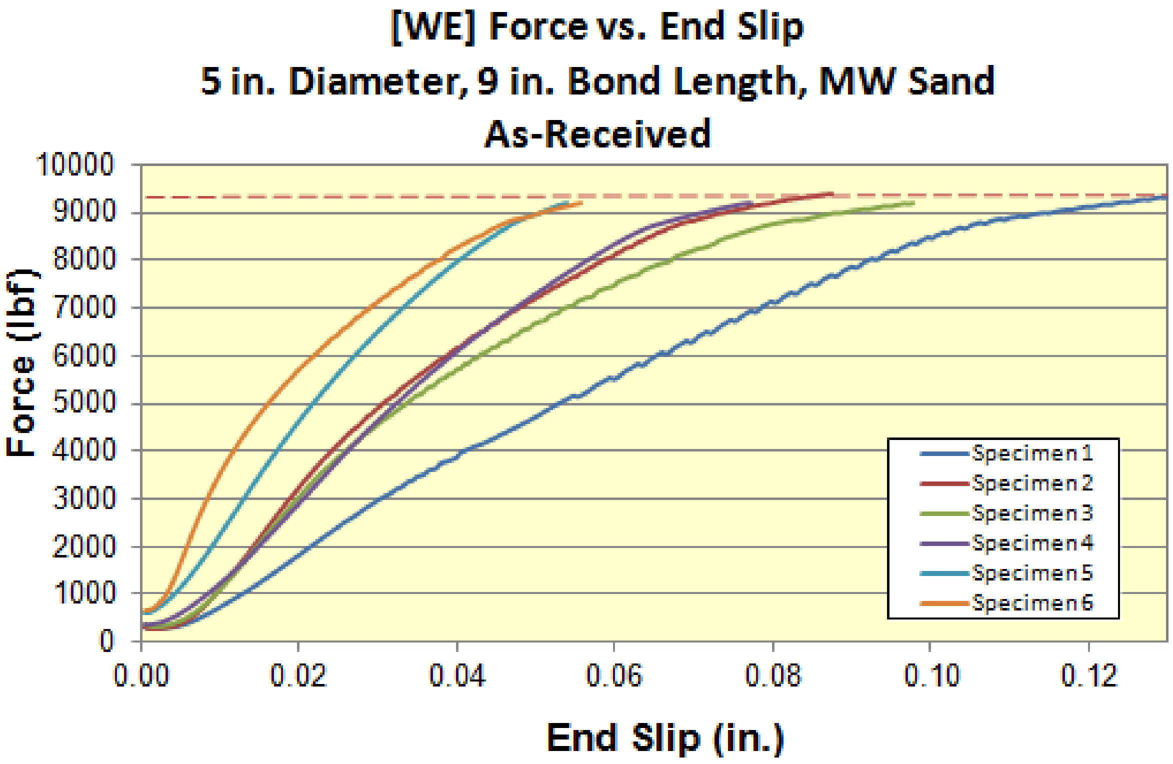


Figure B.5 Midwest sand [WE] force vs. end slip individual graphs

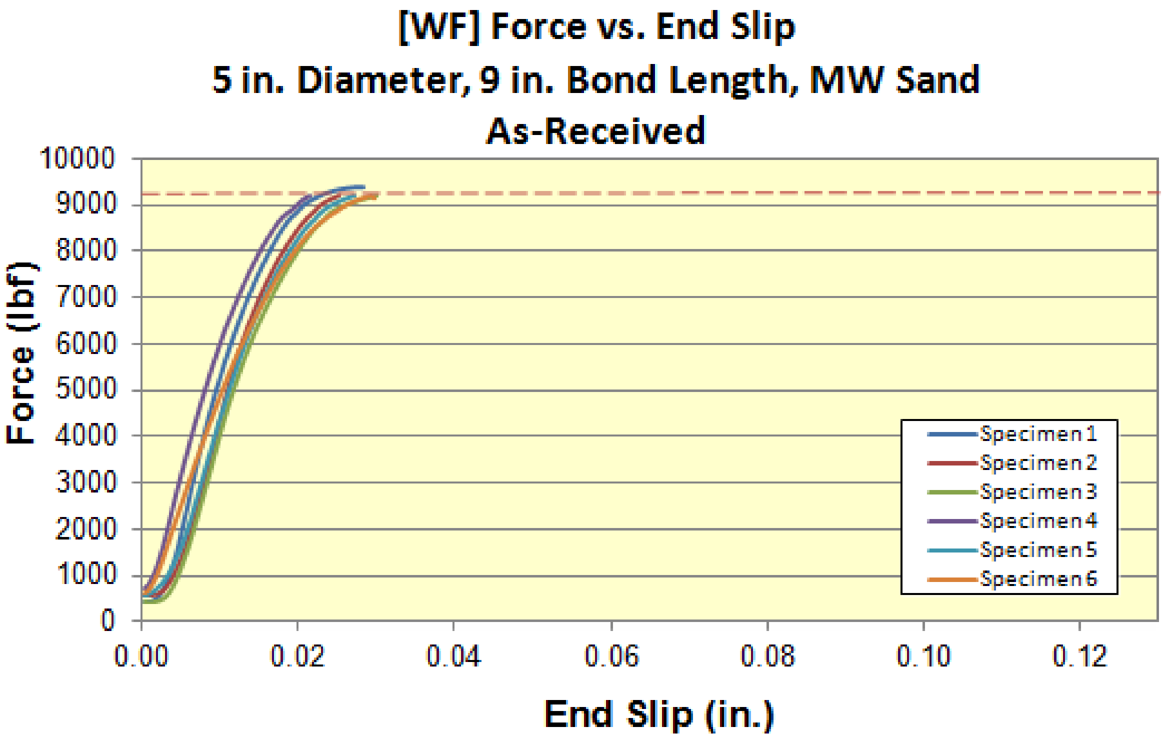


Figure B.6 Midwest sand [WF] force vs. end slip individual graphs

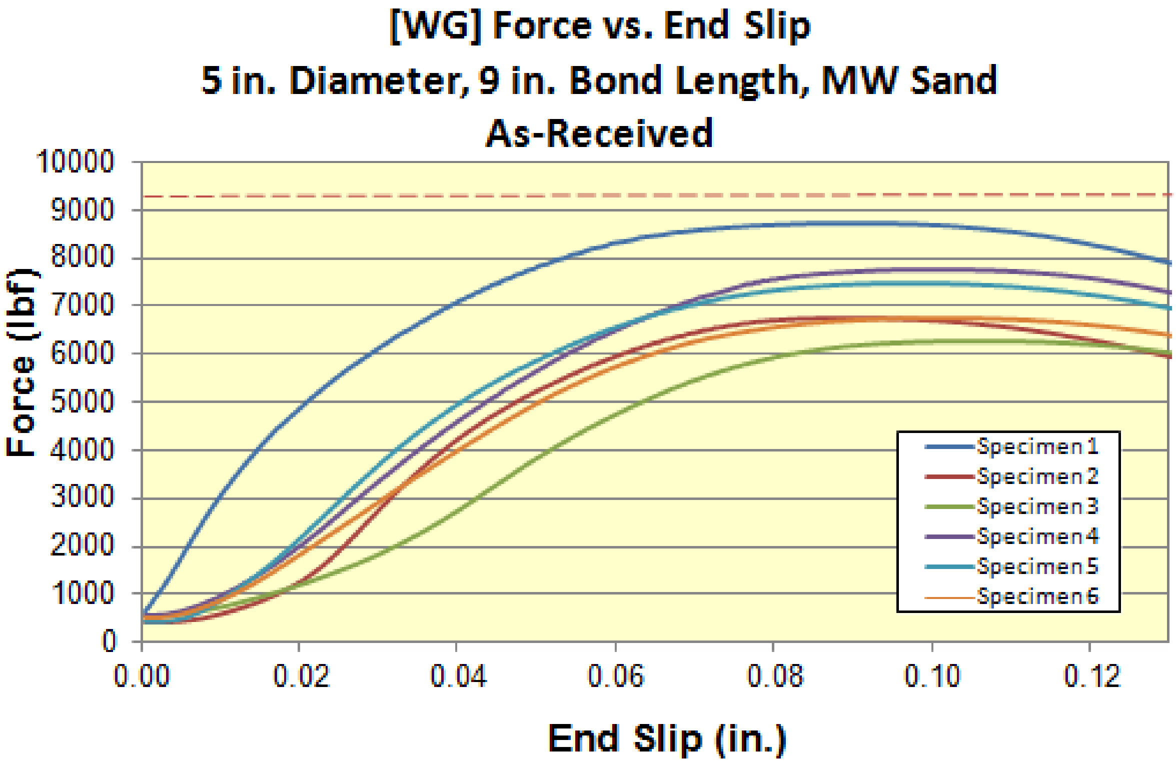


Figure B.7 Midwest sand [WG] force vs. end slip individual graphs

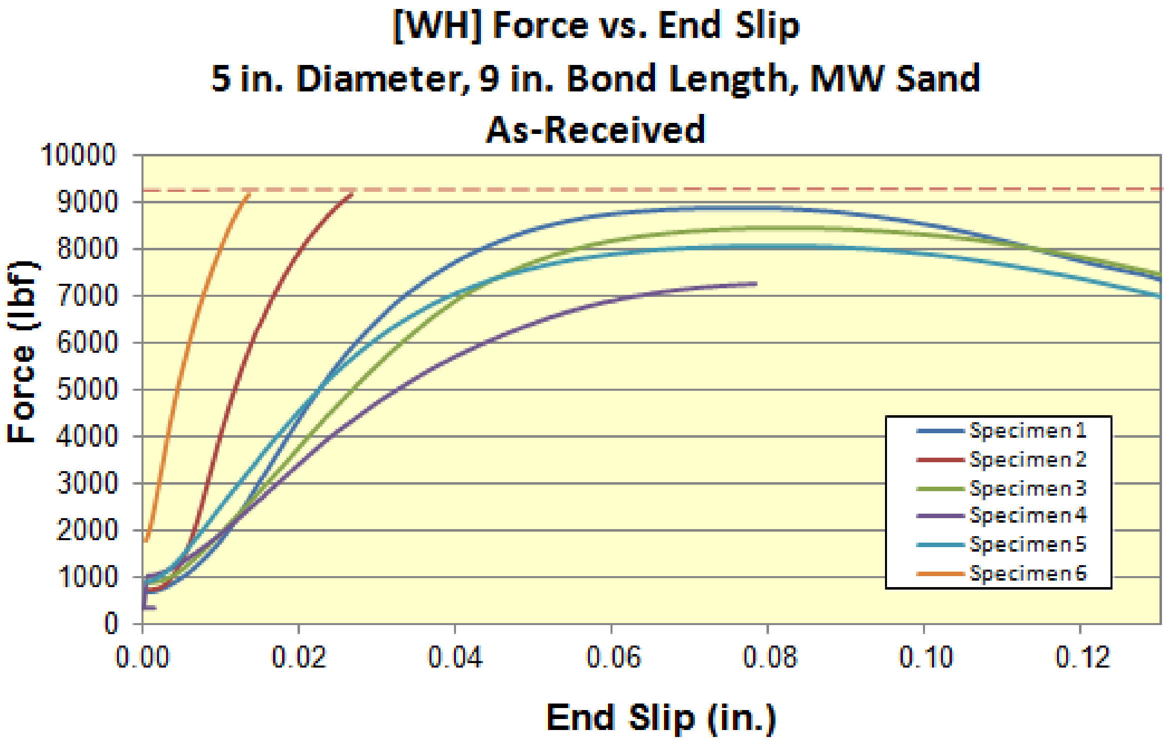


Figure B.8 Midwest sand [WH] force vs. end slip individual graphs

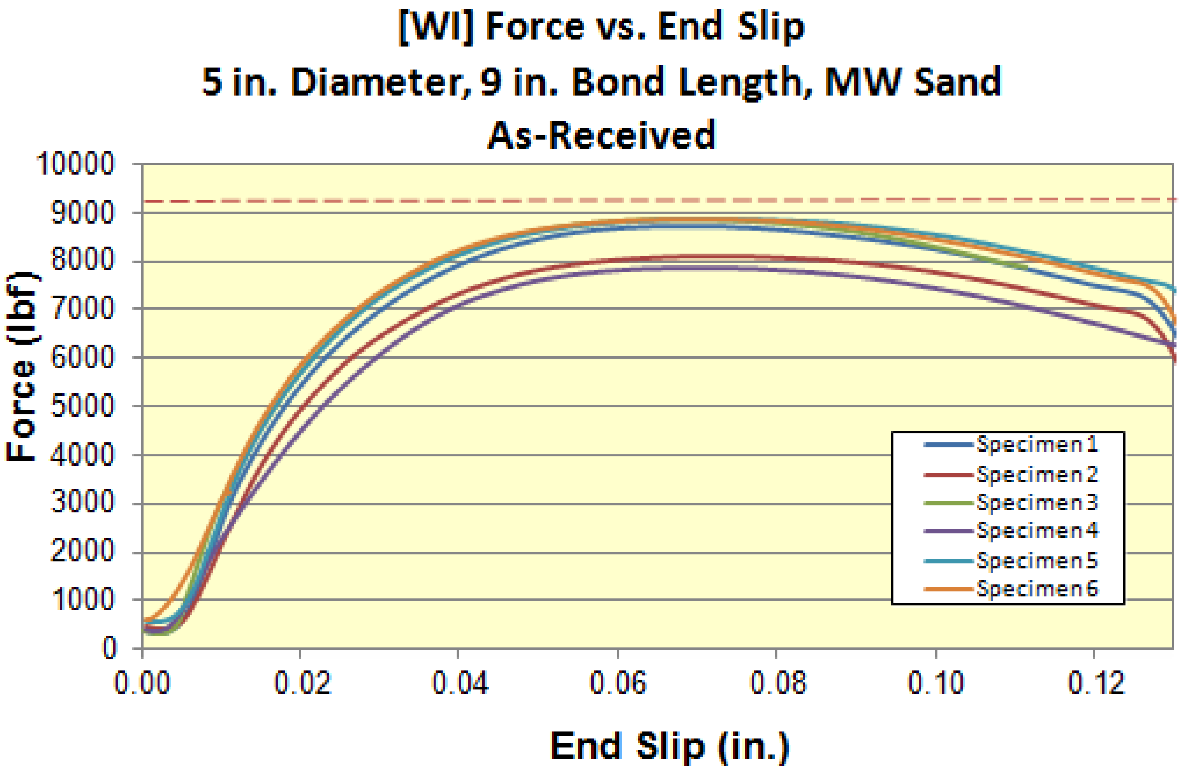


Figure B.9 Midwest sand [WI] force vs. end slip individual graphs

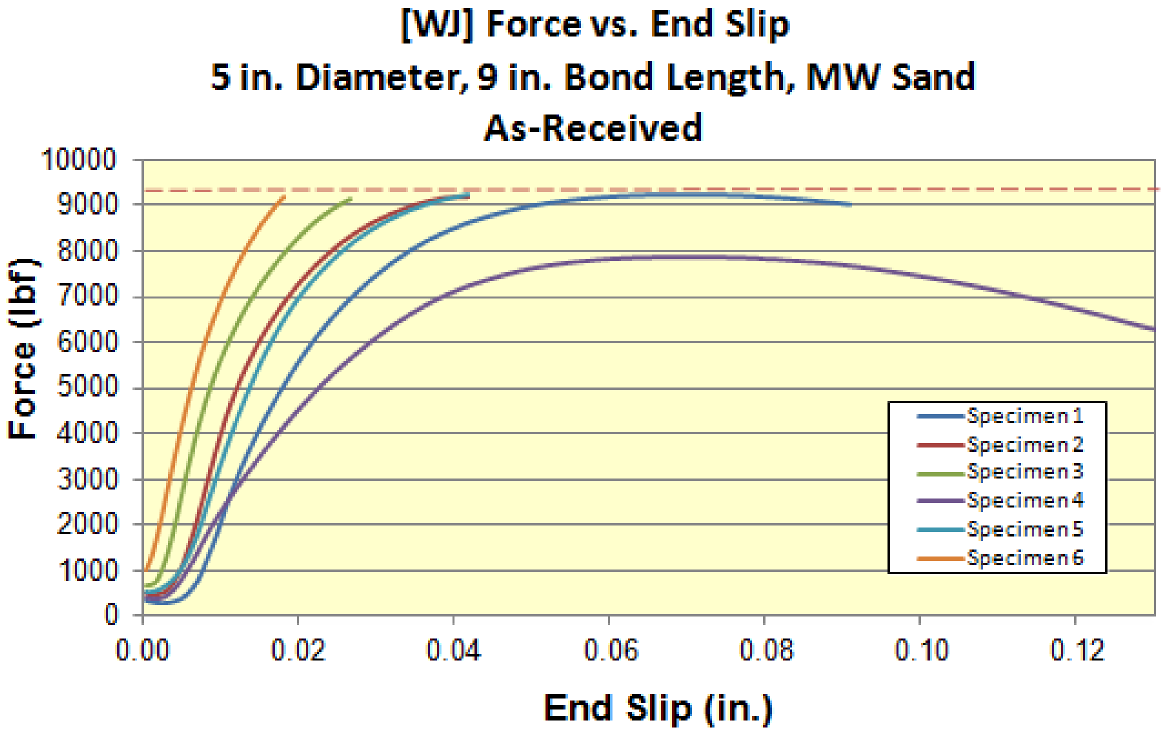


Figure B.10 Midwest sand [WJ] force vs. end slip individual graphs

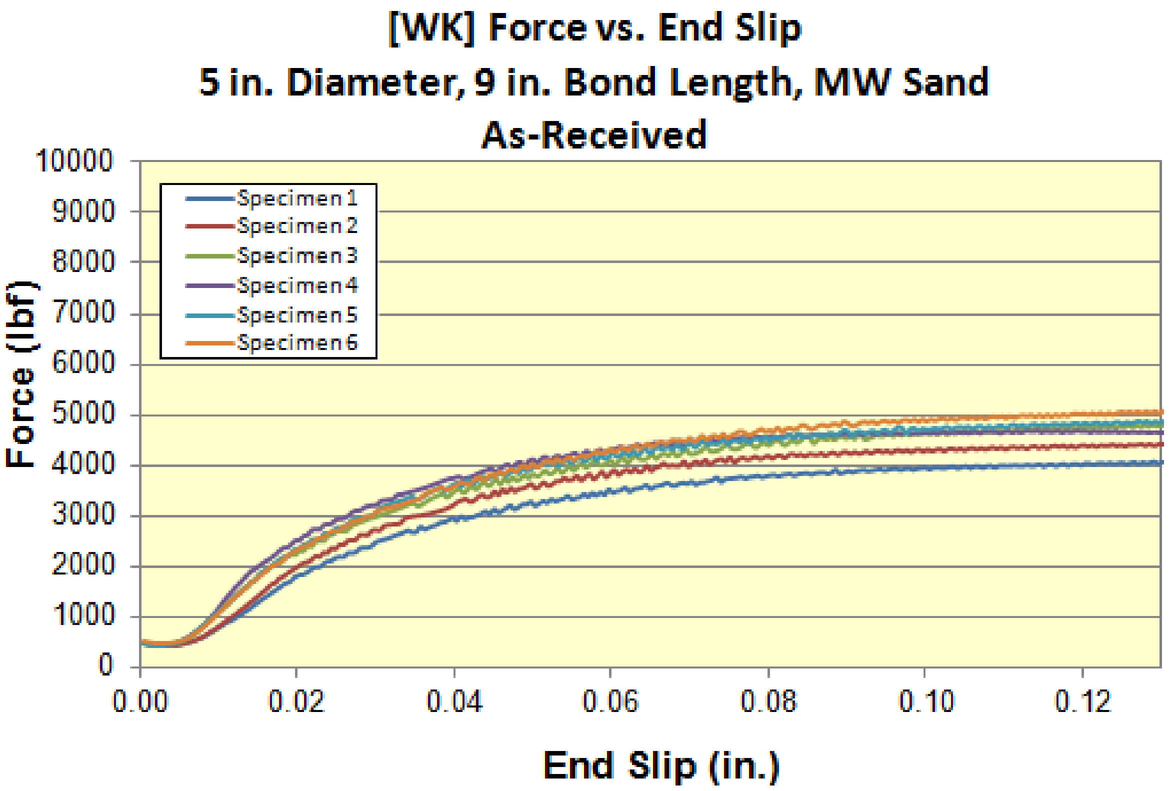


Figure B.11 Midwest sand [WK] force vs. end slip individual graphs

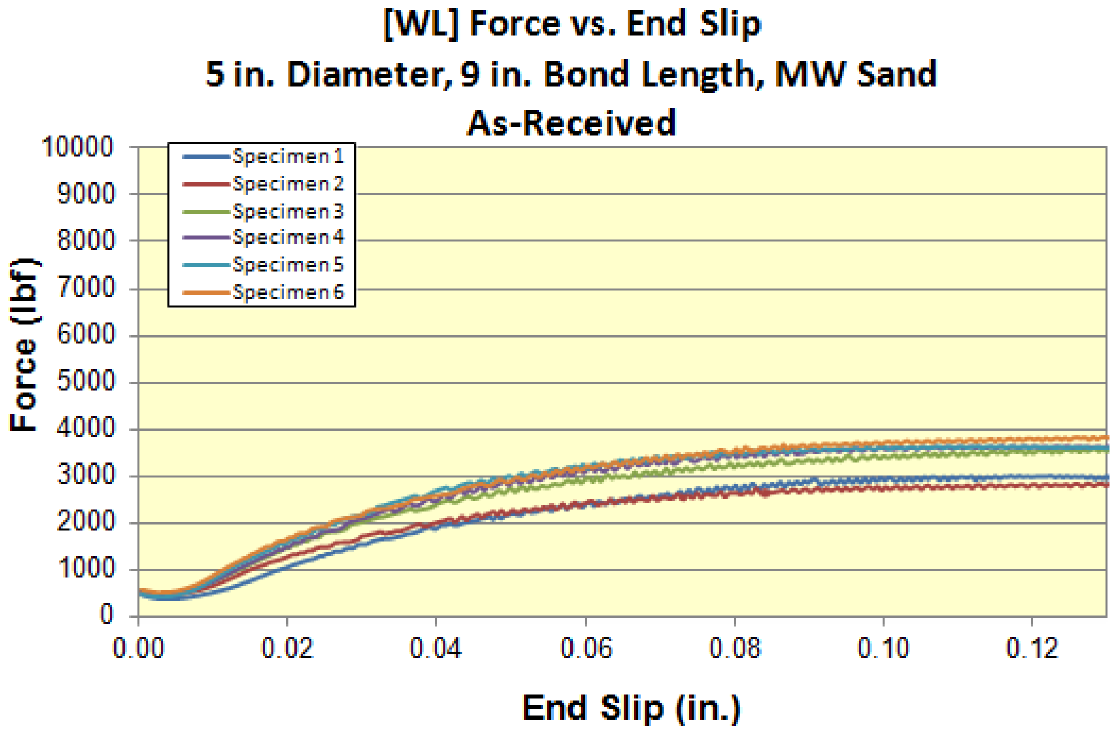


Figure B.12 Midwest sand [WL] force vs. end slip individual graphs

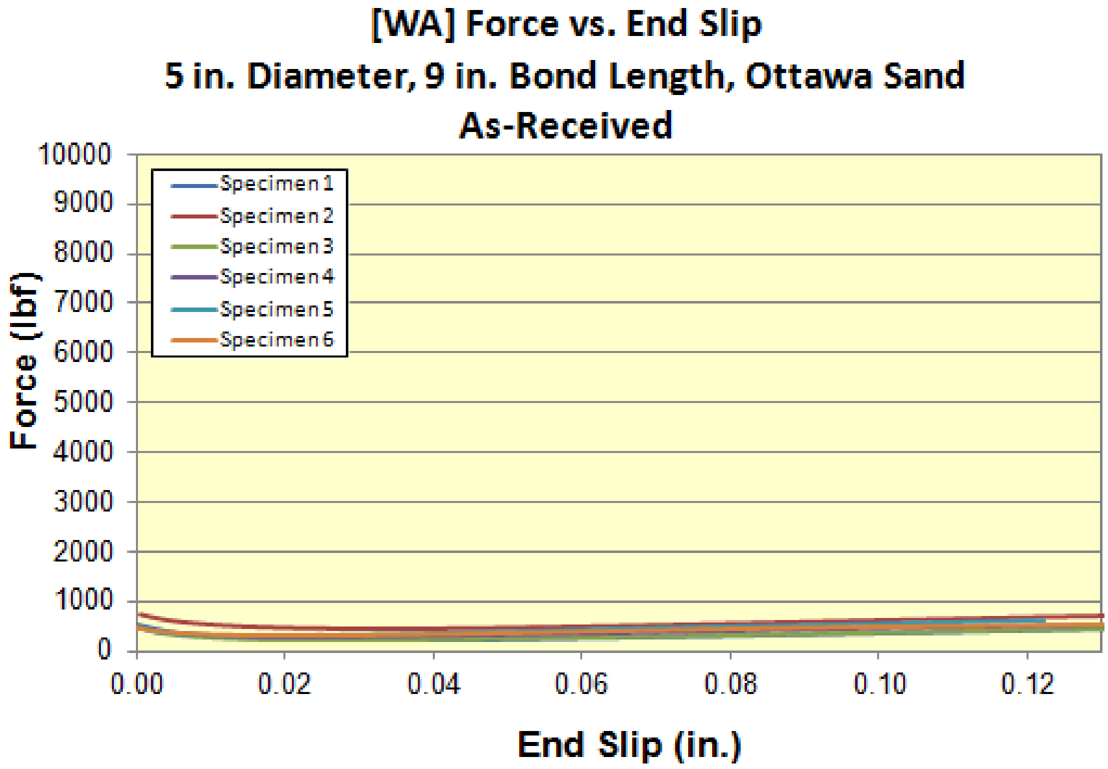


Figure B.13 Ottawa sand [WA] force vs. end slip individual graphs

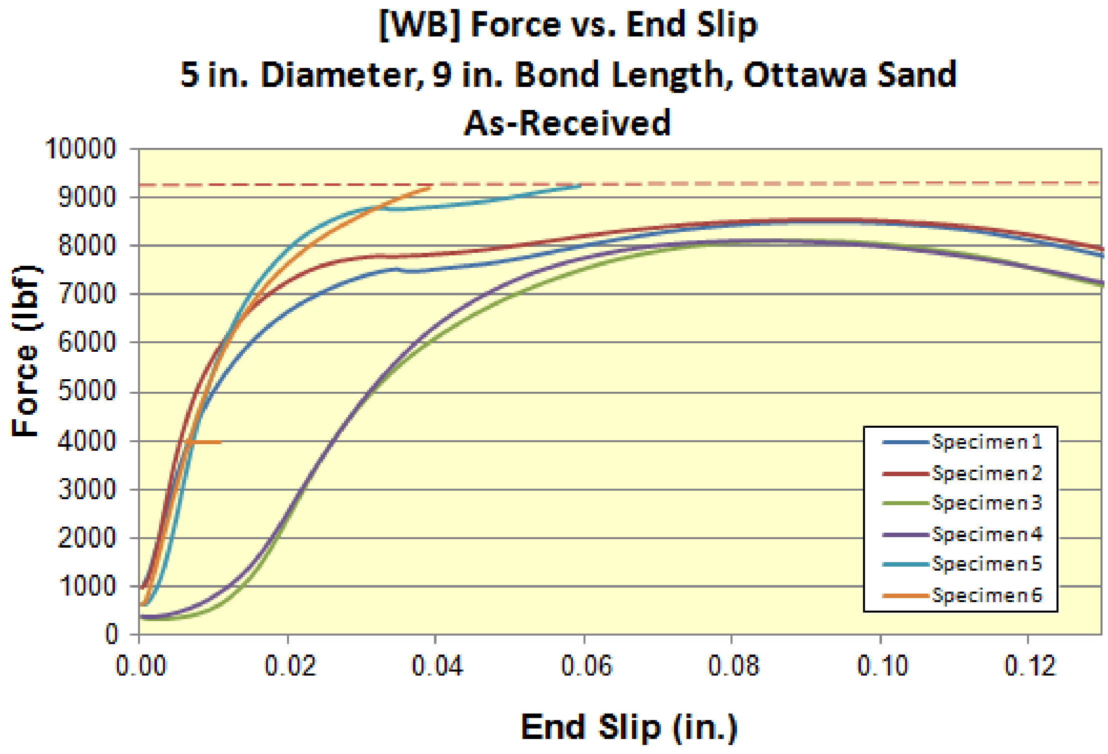


Figure B.14 Ottawa sand [WB] force vs. end slip individual graphs

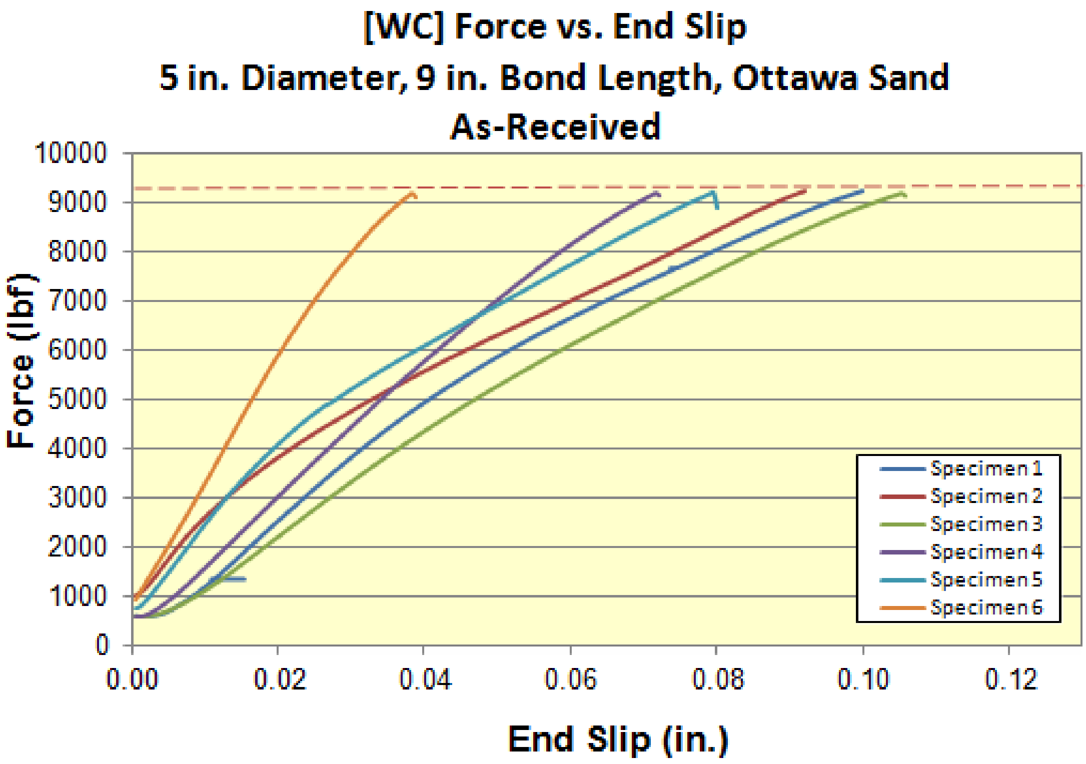


Figure B.15 Ottawa sand [WC] force vs. end slip individual graphs

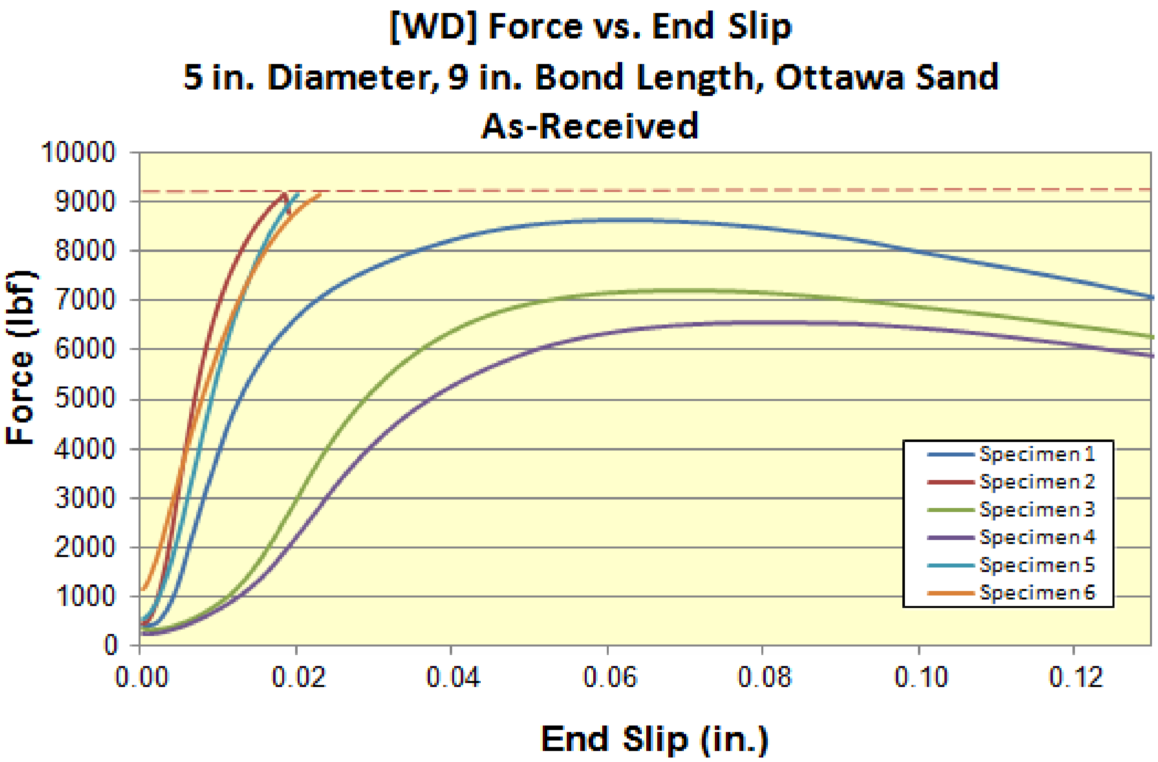


Figure B.16 Ottawa sand [WD] force vs. end slip individual graphs

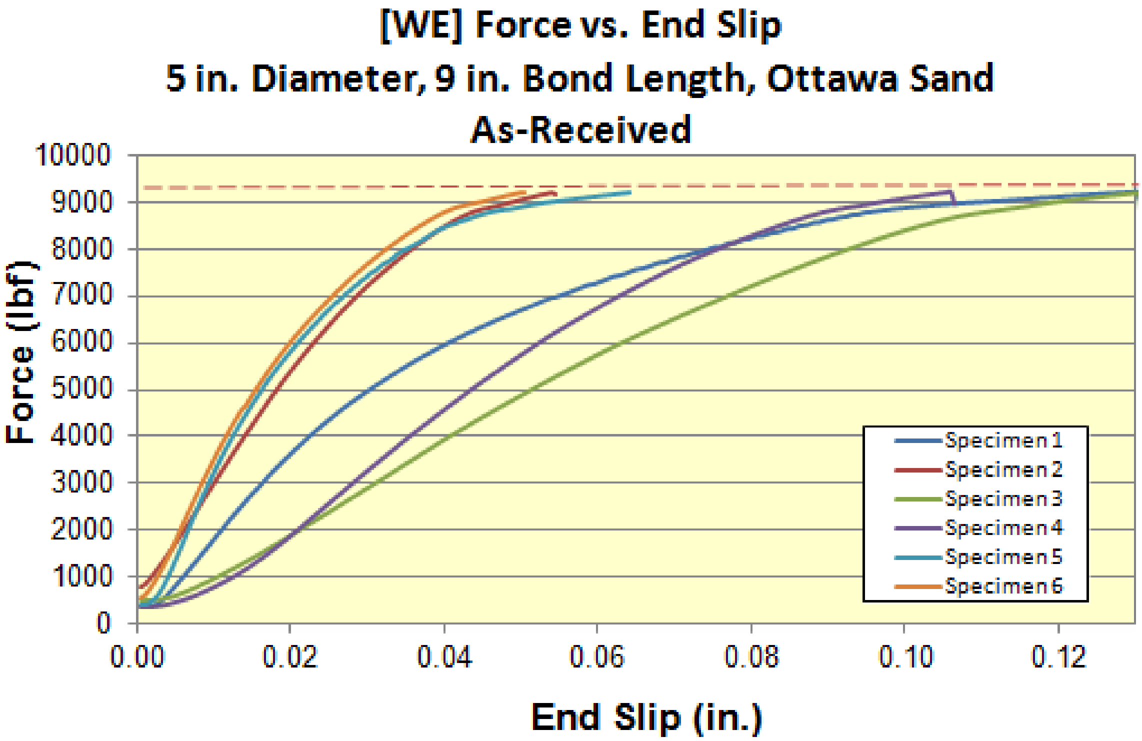


Figure B.17 Ottawa sand [WE] force vs. end slip individual graphs

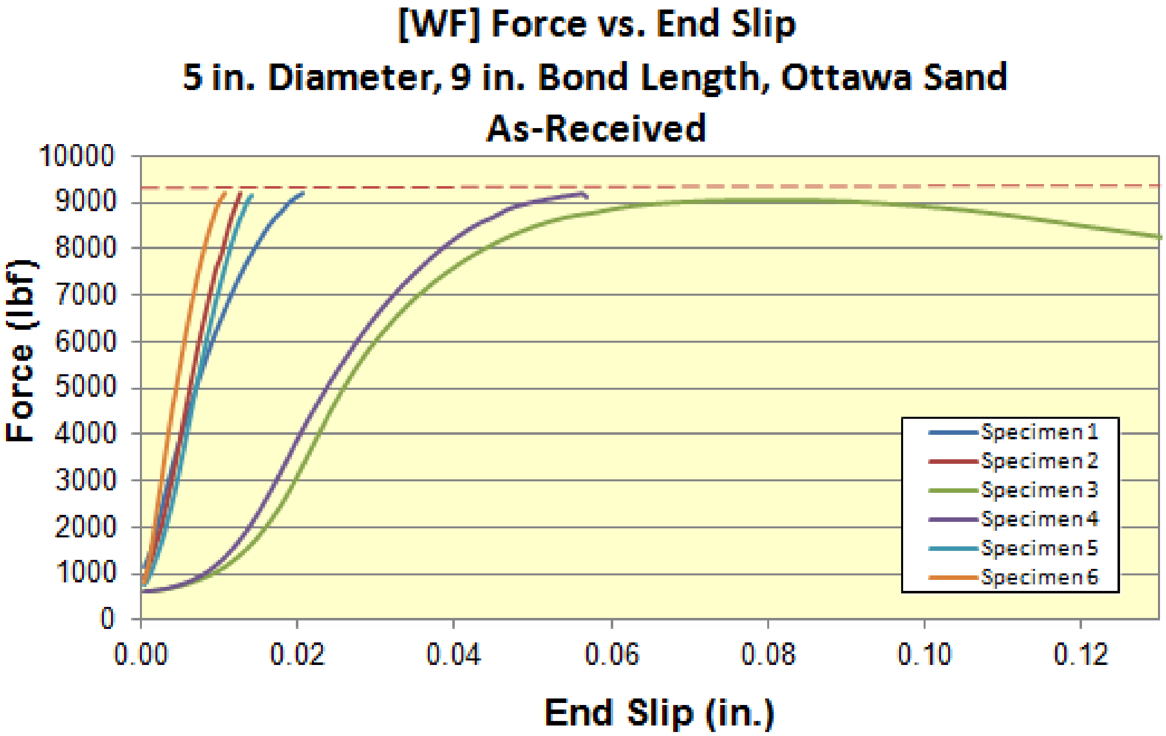


Figure B.18 Ottawa sand [WF] force vs. end slip individual graphs

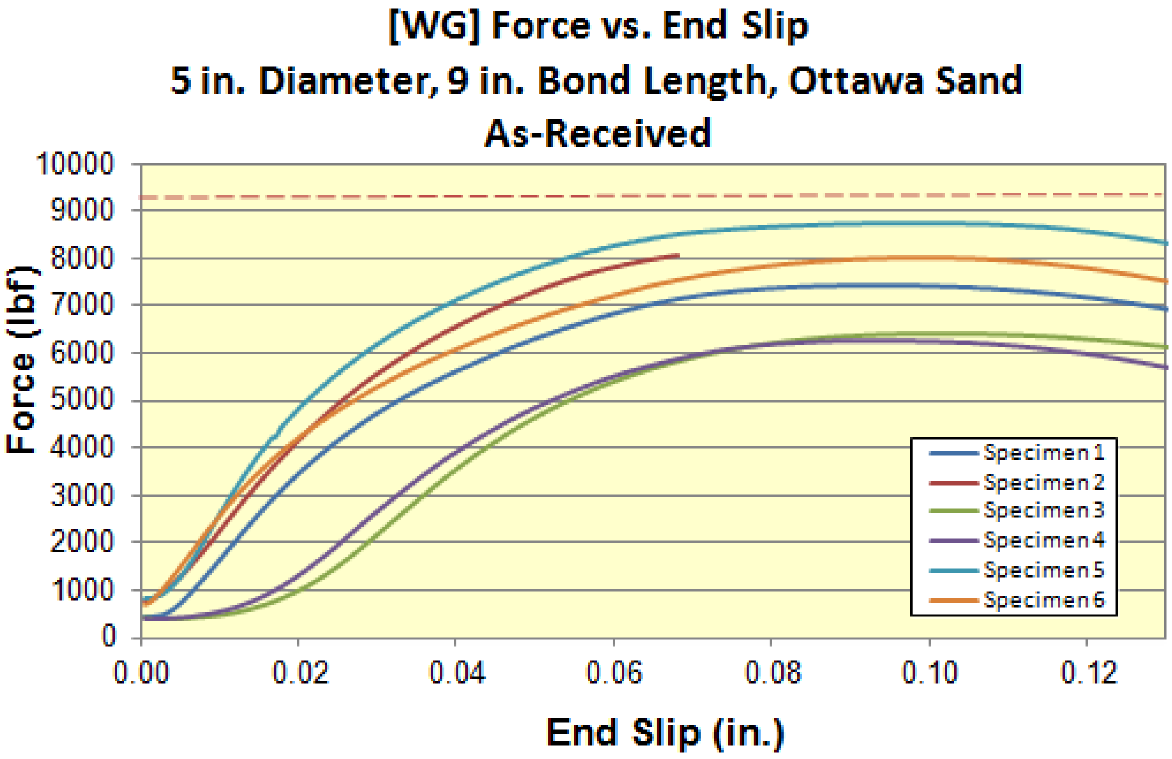


Figure B.19 Ottawa sand [WG] force vs. end slip individual graphs

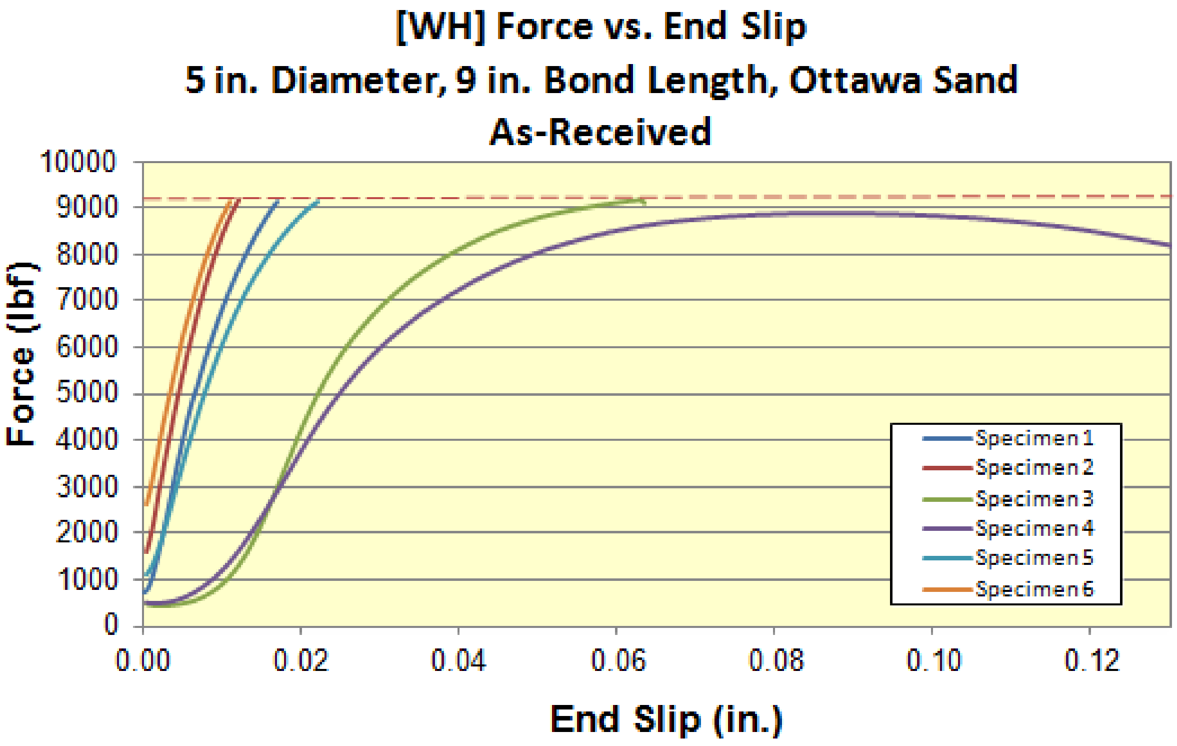


Figure B.20 Ottawa sand [WH] force vs. end slip individual graphs

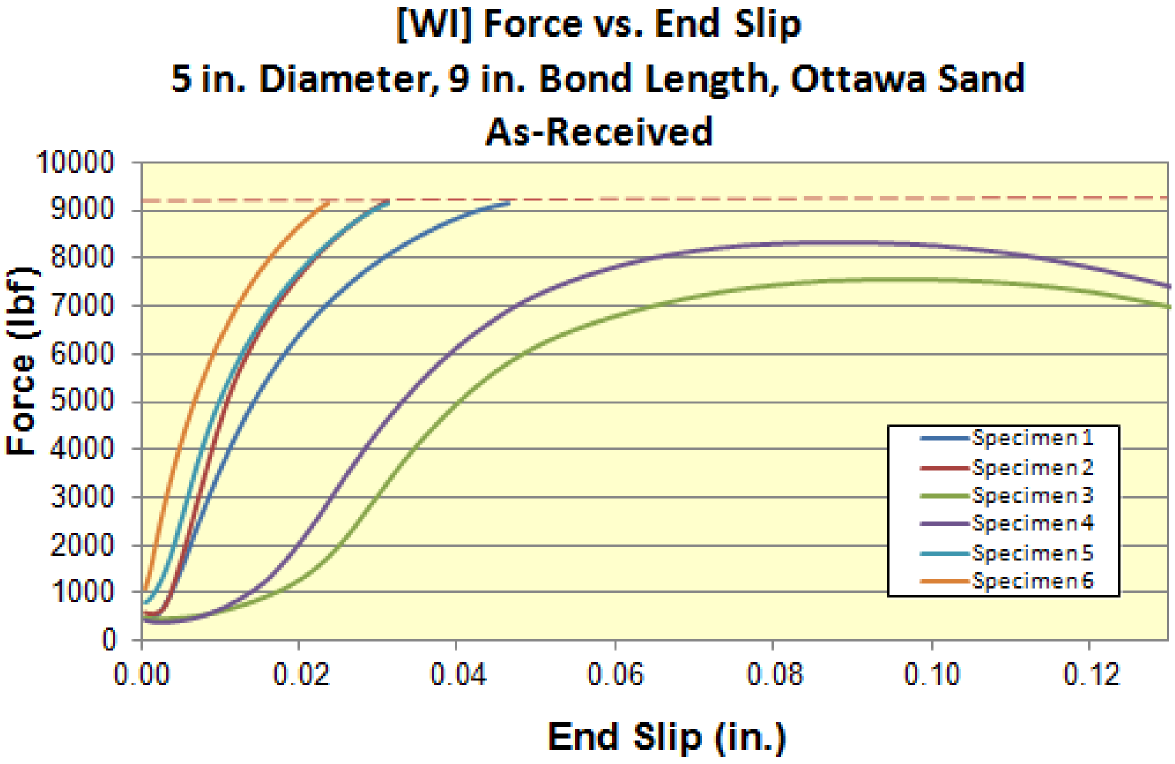


Figure B.21 Ottawa sand [WI] force vs. end slip individual graphs

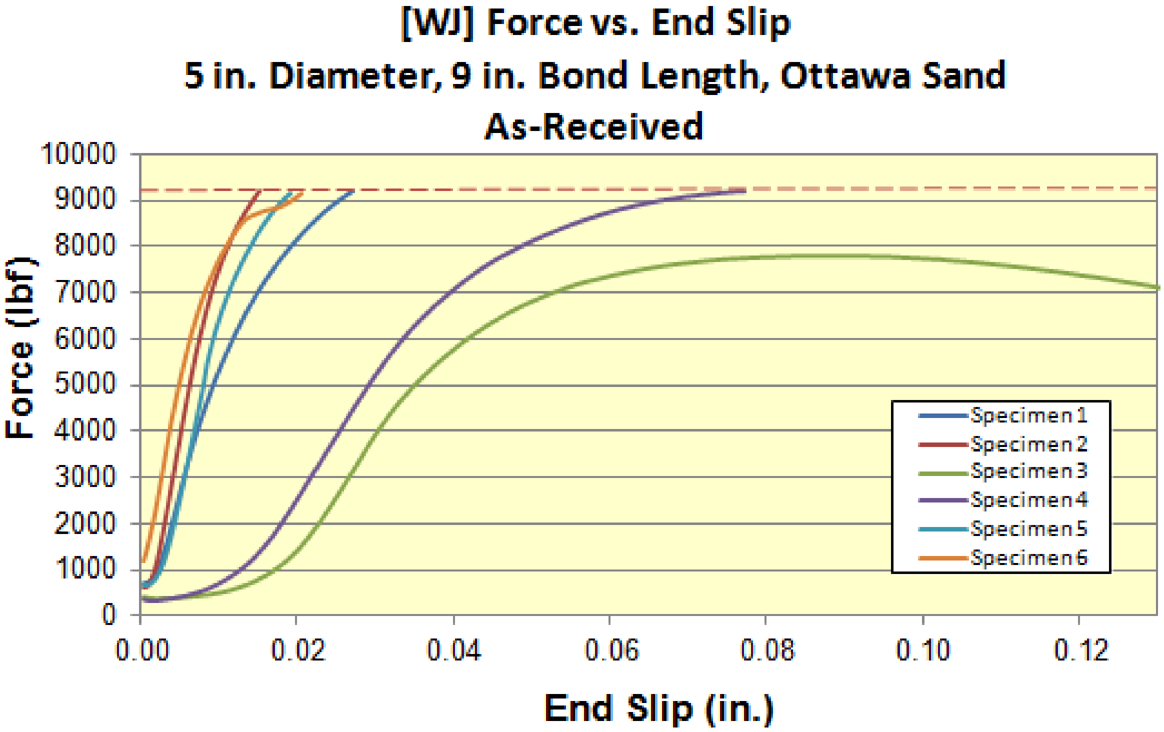


Figure B.22 Ottawa sand [WJ] force vs. end slip individual graphs

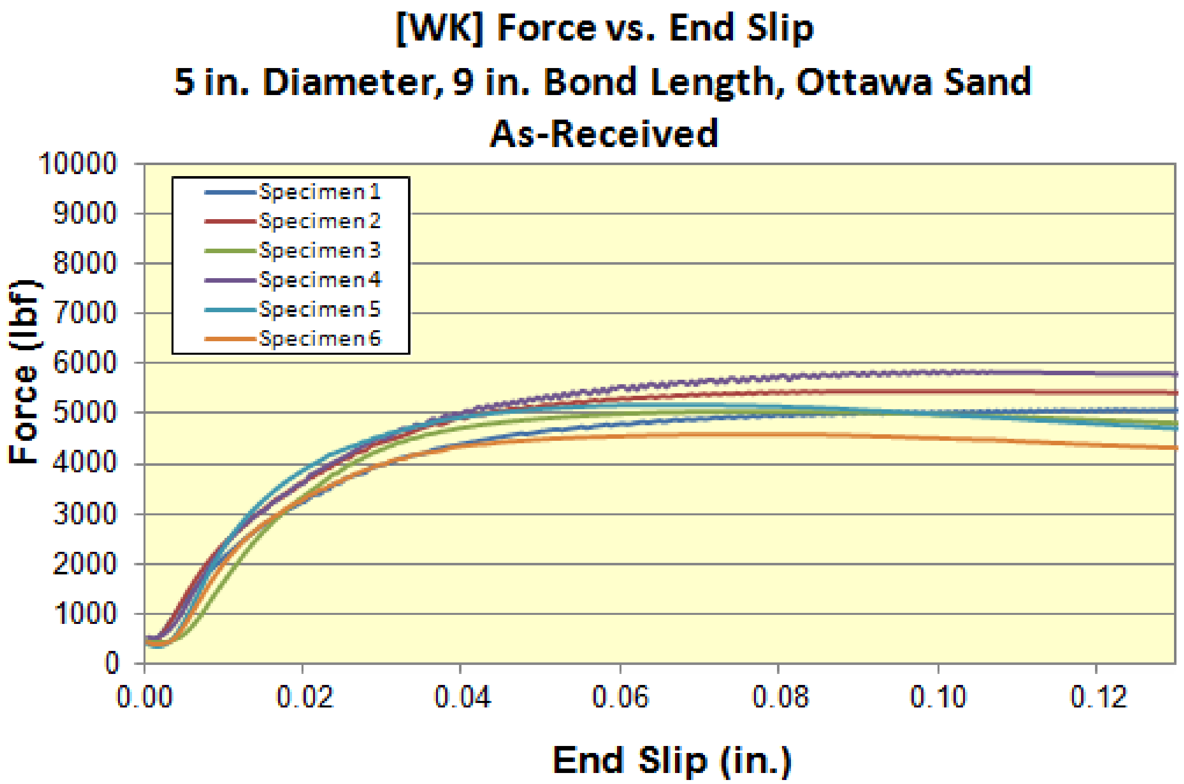


Figure B.23 Ottawa sand [WK] force vs. end slip individual graphs

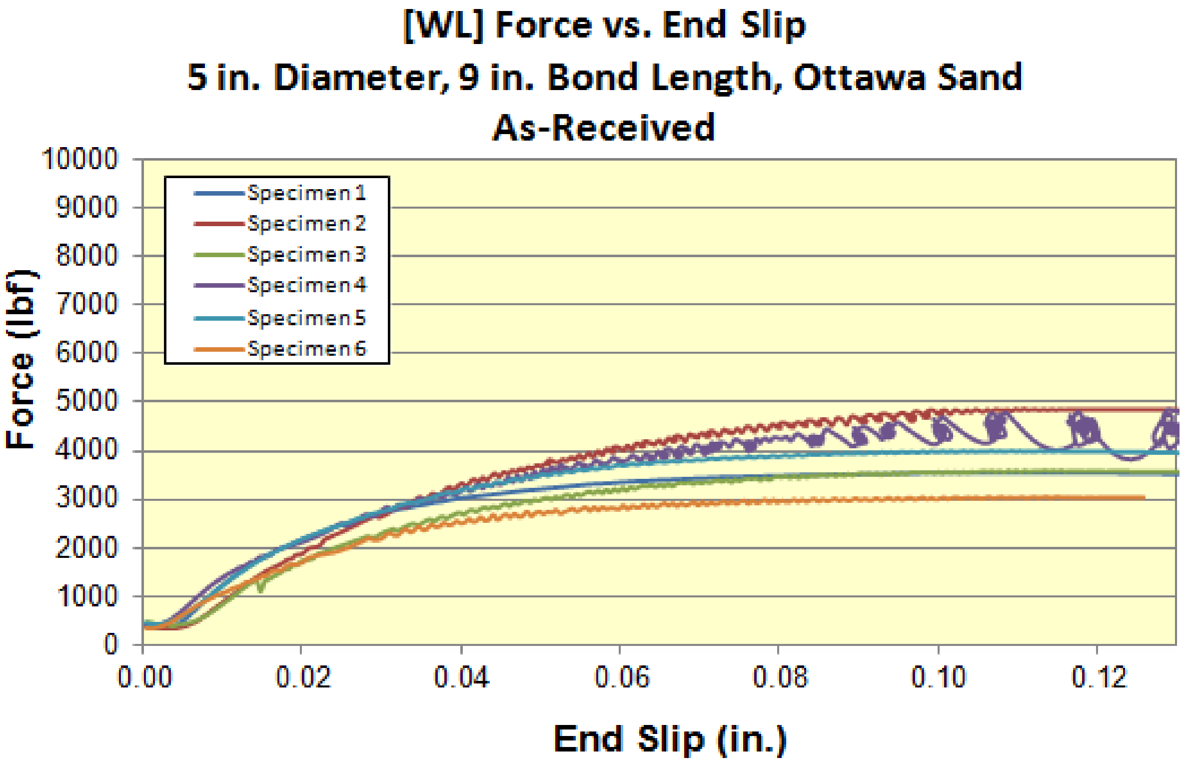


Figure B.24 Ottawa sand [WL] force vs. end slip individual graphs

Appendix C - Wire Test Development Force at Certain End Slips Analysis

Table C.1 Test development analysis, pullout force at 0.01 in. end slip (Midwest sand)

As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Midwest Sand
Pullout Force at 0.01 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	282	43	15.3	16.3
[WB]	3243	510	15.7	11.6
[WC]	1830	402	22.0	8.8
[WD]	2674	1668	62.4	11.1
[WE]	1582	930	58.8	7.4
[WF]	4800	784	16.3	8.5
[WG]	1143	815	71.3	11.8
[WH]	3531	2262	64.1	7.5
[WI]	2480	337	13.6	10.1
[WJ]	3807	1745	45.8	9.0
[WK]	944	138	14.6	14.0
[WL]	688	108	15.6	18.7

Note: Sample Size = 6

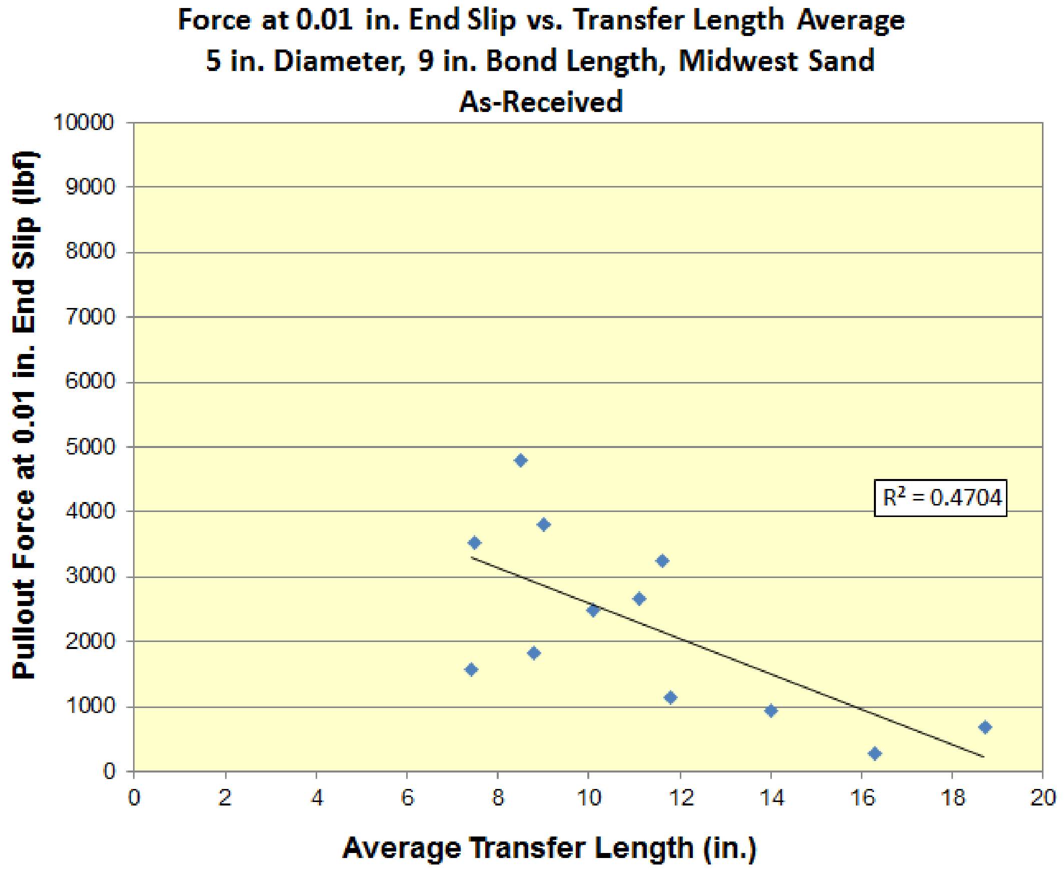


Figure C.1 Test development analysis, pullout force at 0.01 in. end slip (Midwest sand)

Table C.2 Test development analysis, pullout force at 0.02 in. end slip (Midwest sand)

As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Midwest Sand
Pullout Force at 0.02 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	229	26	11.5	16.3
[WB]	5952	307	5.2	11.6
[WC]	2752	603	21.9	8.8
[WD]	5607	1742	31.1	11.1
[WE]	3504	1256	35.9	7.4
[WF]	8499	438	5.2	8.5
[WG]	2176	1227	56.4	11.8
[WH]	4119	2367	57.5	7.5
[WI]	5253	447	8.5	10.1
[WJ]	6438	1336	20.7	9.0
[WK]	2186	241	11.0	14.0
[WL]	1402	200	14.3	18.7

Note: Sample Size = 6, J = 5

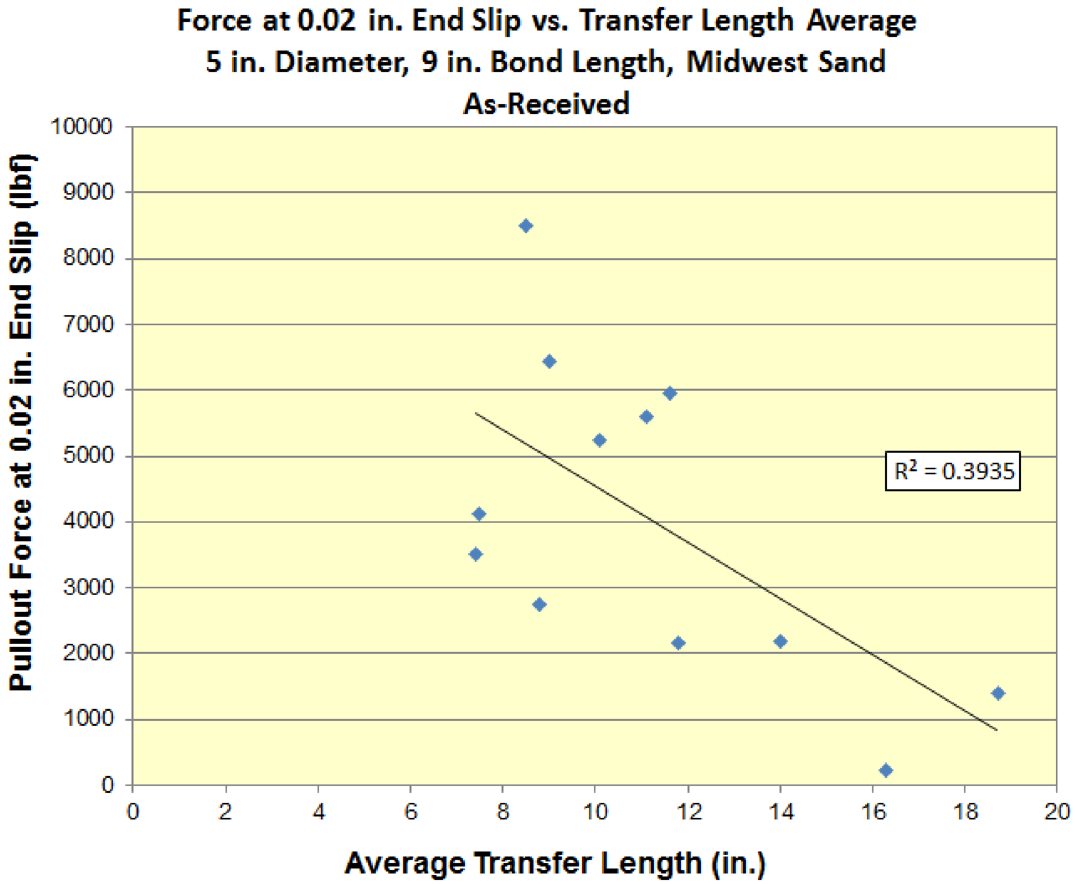


Figure C.2 Test development analysis, pullout force at 0.02 in. end slip (Midwest sand)

Table C.3 Test development analysis, pullout force at 0.03 in. end slip (Midwest sand)

As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Midwest Sand
Pullout Force at 0.03 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	208	21	10.0	16.3
[WB]	7129	274	3.8	11.6
[WC]	3405	786	23.1	8.8
[WD]	6386	2598	40.7	11.1
[WE]	5091	1361	26.7	7.4
[WF]	9155	15	0.2	8.5
[WG]	3410	1325	38.9	11.8
[WH]	5809	3236	55.7	7.5
[WI]	6853	460	6.7	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	2880	258	9.0	14.0
[WL]	1946	239	12.3	18.7

Note: Sample Size = 6, D = 5, F = 2, H = 4, J = 5

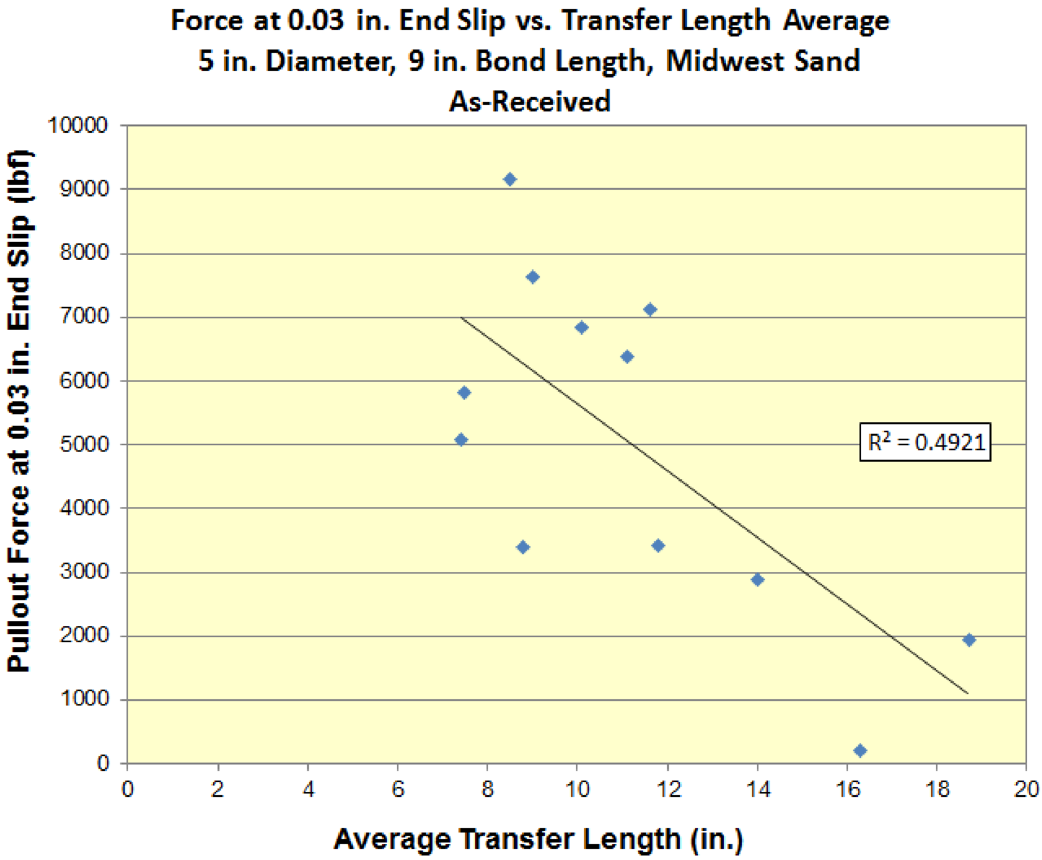


Figure C.3 Test development analysis, pullout force at 0.03 in. end slip (Midwest sand)

Table C.4 Test development analysis, pullout force at 0.04 in. end slip (Midwest sand)

As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Midwest Sand
Pullout Force at 0.04 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	200	19	9.7	16.3
[WB]	7782	217	2.8	11.6
[WC]	3978	960	24.1	8.8
[WD]	6961	786	11.3	11.1
[WE]	6341	1466	23.1	7.4
[WF]				
[WG]	4578	1305	28.5	11.8
[WH]	6920	728	10.5	7.5
[WI]	7791	429	5.5	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	3436	269	7.8	14.0
[WL]	2324	298	12.8	18.7

Note: Sample Size = 6, D = 5, F = 0, H = 4, J = 5

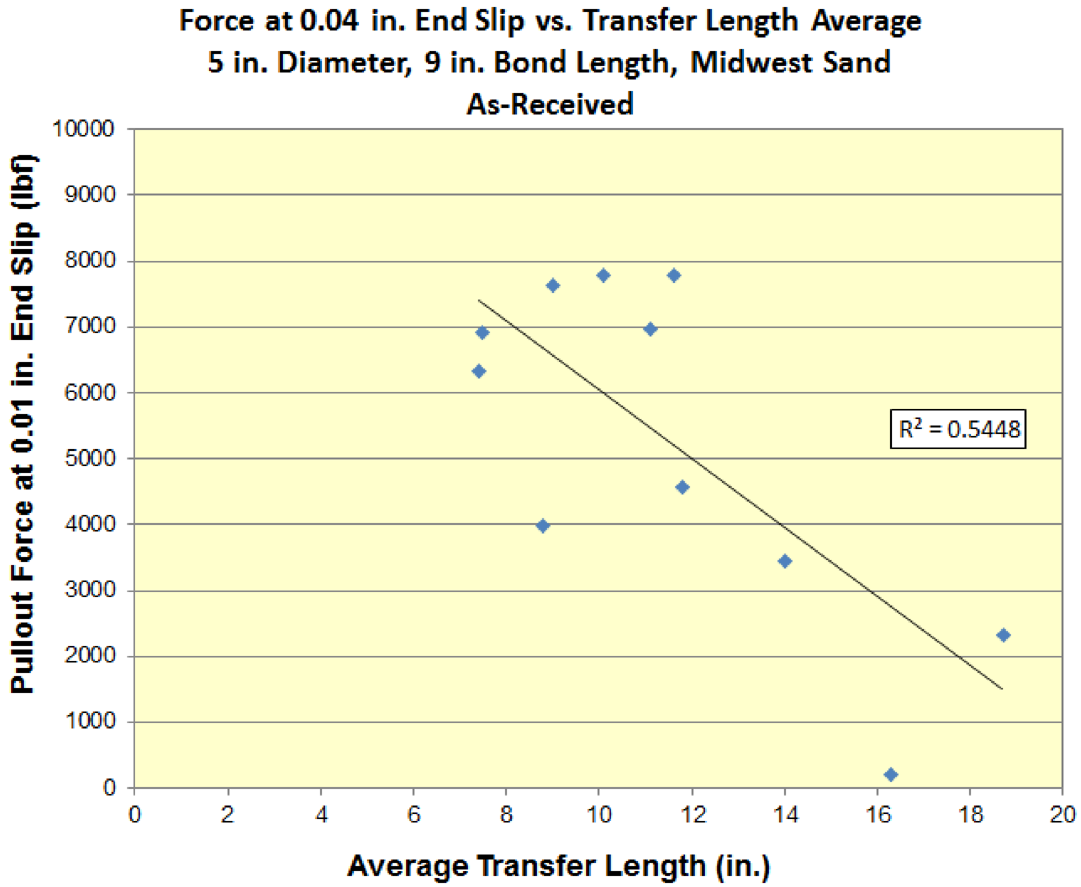
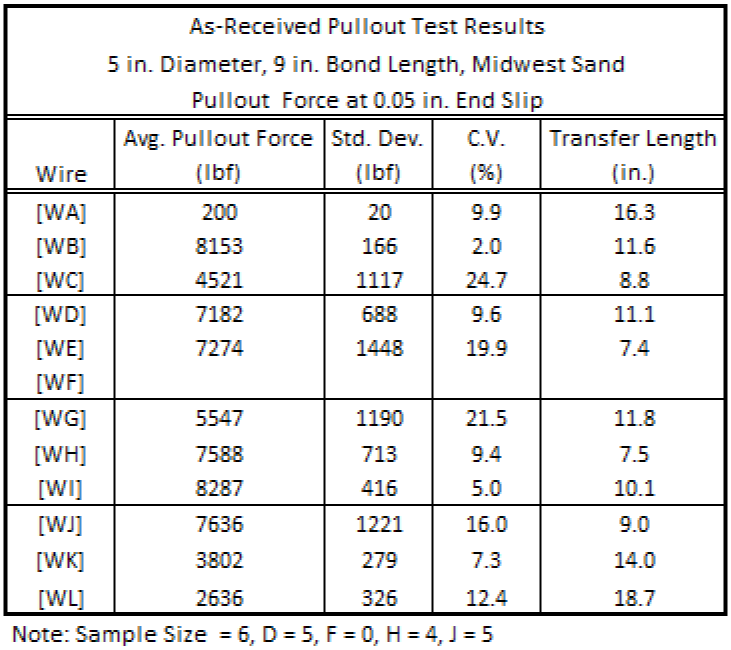


Figure C.4 Test development analysis, pullout force at 0.04 in. end slip (Midwest sand)

Table C.5 Test development analysis, pullout force at 0.05 in. end slip (Midwest sand)



As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Midwest Sand
Pullout Force at 0.05 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	200	20	9.9	16.3
[WB]	8153	166	2.0	11.6
[WC]	4521	1117	24.7	8.8
[WD]	7182	688	9.6	11.1
[WE]	7274	1448	19.9	7.4
[WF]				
[WG]	5547	1190	21.5	11.8
[WH]	7588	713	9.4	7.5
[WI]	8287	416	5.0	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	3802	279	7.3	14.0
[WL]	2636	326	12.4	18.7

Note: Sample Size = 6, D = 5, F = 0, H = 4, J = 5

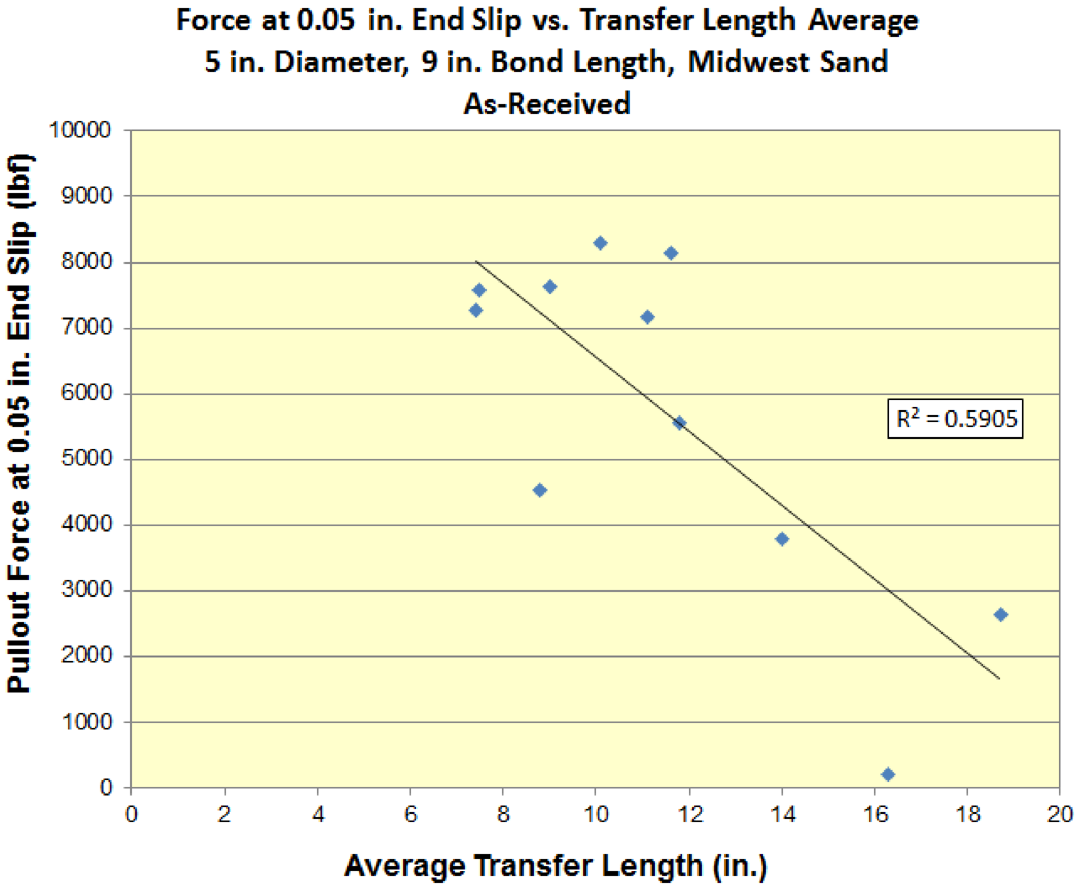


Figure C.5 Test development analysis, pullout force at 0.05 in. end slip (Midwest sand)

Table C.6 Test development analysis, pullout force at 0.06 in. end slip (Midwest sand)

As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Midwest Sand
Pullout Force at 0.06 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	204	20	10.0	16.3
[WB]	8353	134	1.6	11.6
[WC]	5053	1263	25.0	8.8
[WD]	7234	633	8.8	11.1
[WE]	7342	1096	14.9	7.4
[WF]				
[WG]	6302	1076	17.1	11.8
[WH]	7954	666	8.4	7.5
[WI]	8493	411	4.8	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	4047	282	7.0	14.0
[WL]	2849	360	12.6	18.7

Note: Sample Size = 6, D = 5, E = 4, F = 0, H = 4, J = 5

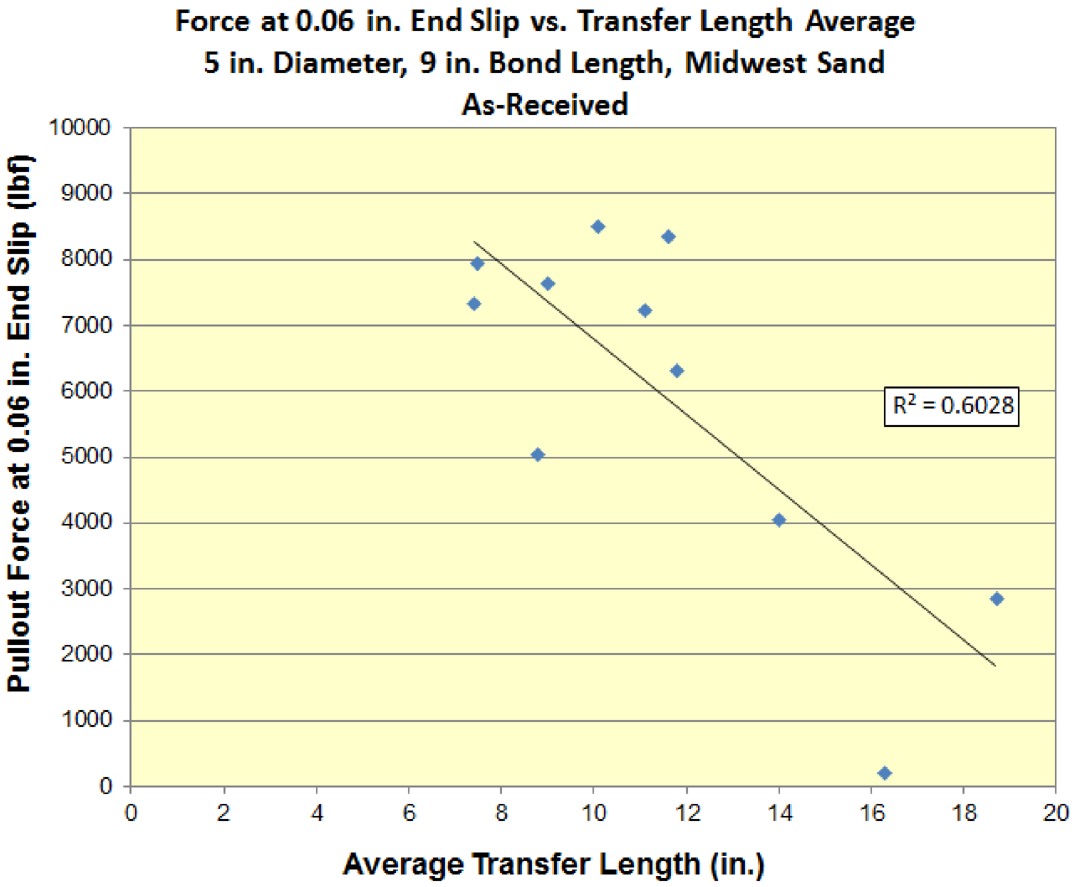


Figure C.6 Test development analysis, pullout force at 0.06 in. end slip (Midwest sand)

Table C.7 Test development analysis, pullout force at 0.07 in. end slip (Midwest sand)

As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Midwest Sand
Pullout Force at 0.07 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	212	22	10.4	16.3
[WB]	8440	114	1.4	11.6
[WC]	5554	1395	25.1	8.8
[WD]	7189	596	8.3	11.1
[WE]	8079	1039	12.9	7.4
[WF]				
[WG]	6801	955	14.0	11.8
[WH]	8118	620	7.6	7.5
[WI]	8545	407	4.8	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	4209	313	7.4	14.0
[WL]	3031	382	12.6	18.7

Note: Sample Size = 6, D = 5, E = 4, F = 0, H = 4, J = 5

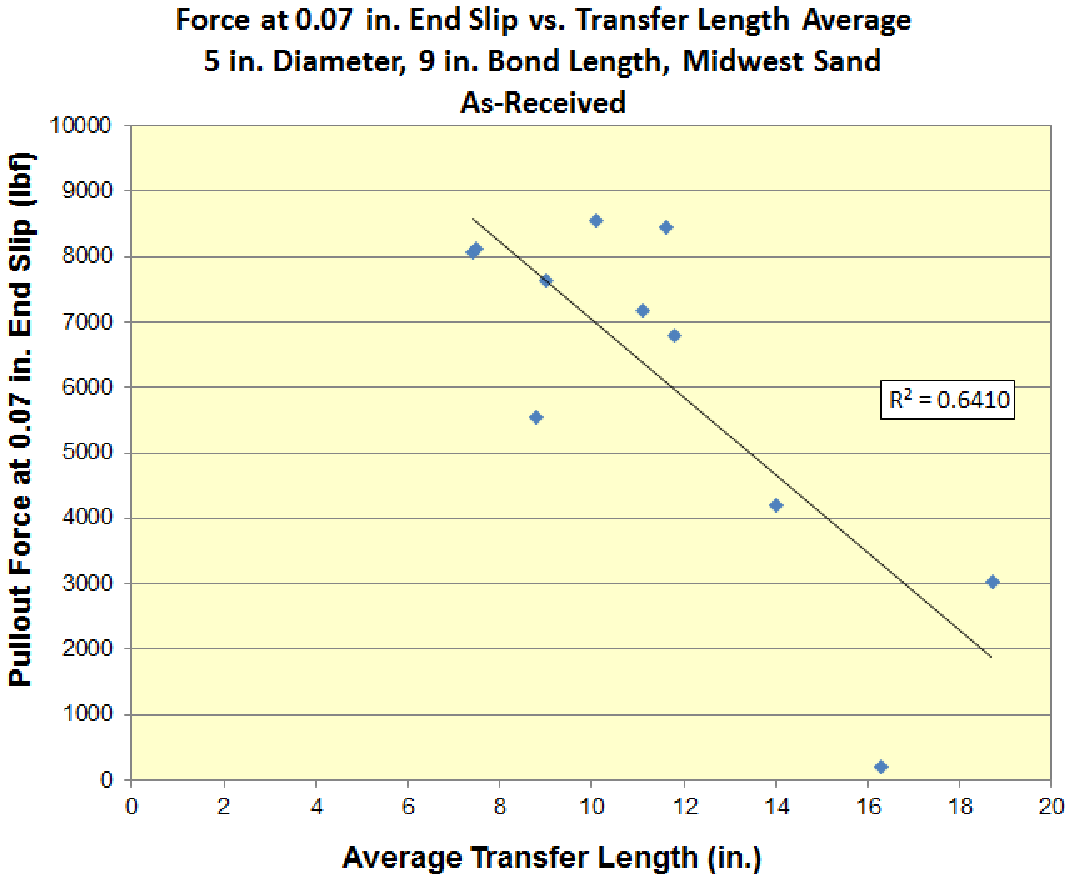
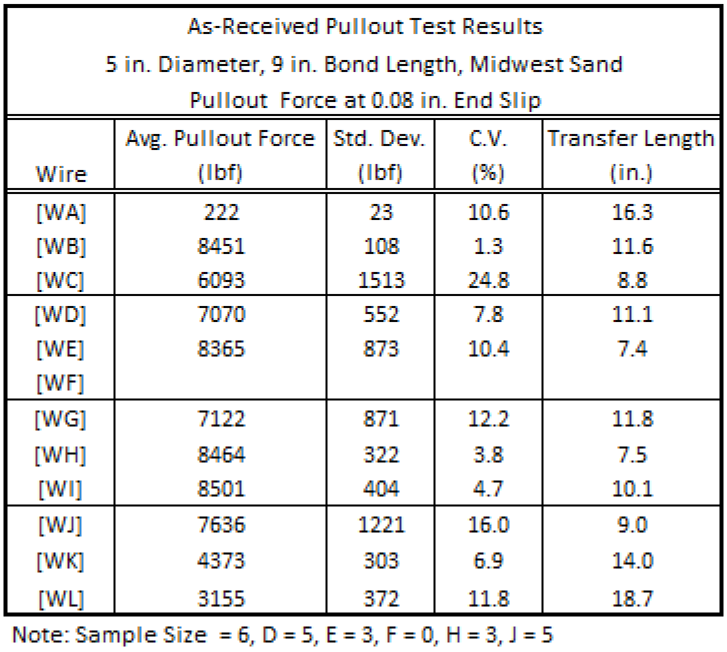


Figure C.7 Test development analysis, pullout force at 0.06 in. end slip (Midwest sand)

Table C.8 Test development analysis, pullout force at 0.08 in. end slip (Midwest sand)



As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Midwest Sand
Pullout Force at 0.08 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	222	23	10.6	16.3
[WB]	8451	108	1.3	11.6
[WC]	6093	1513	24.8	8.8
[WD]	7070	552	7.8	11.1
[WE]	8365	873	10.4	7.4
[WF]				
[WG]	7122	871	12.2	11.8
[WH]	8464	322	3.8	7.5
[WI]	8501	404	4.7	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	4373	303	6.9	14.0
[WL]	3155	372	11.8	18.7

Note: Sample Size = 6, D = 5, E = 3, F = 0, H = 3, J = 5

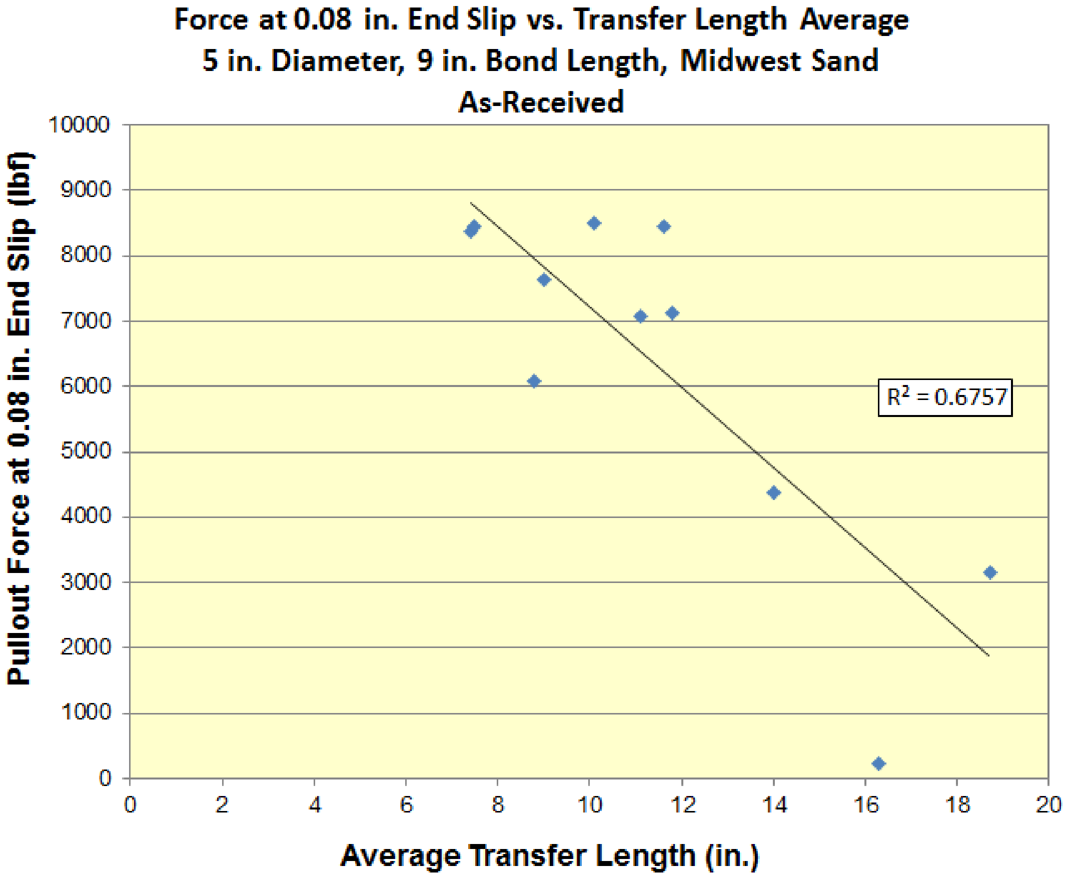


Figure C.8 Test development analysis, pullout force at 0.08 in. end slip (Midwest sand)

Table C.9 Test development analysis, pullout force at 0.09 in. end slip (Midwest sand)

As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Midwest Sand
Pullout Force at 0.09 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	234	26	10.9	16.3
[WB]	8392	102	1.2	11.6
[WC]	6643	1613	24.3	8.8
[WD]	6889	510	7.4	11.1
[WE]	8468	585	6.9	7.4
[WF]				
[WG]	7254	820	11.3	11.8
[WH]	8414	297	3.5	7.5
[WI]	8370	398	4.8	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	4471	319	7.1	14.0
[WL]	3292	348	10.6	18.7

Note: Sample Size = 6, D = 5, E = 1, F = 0, H = 3, J = 5

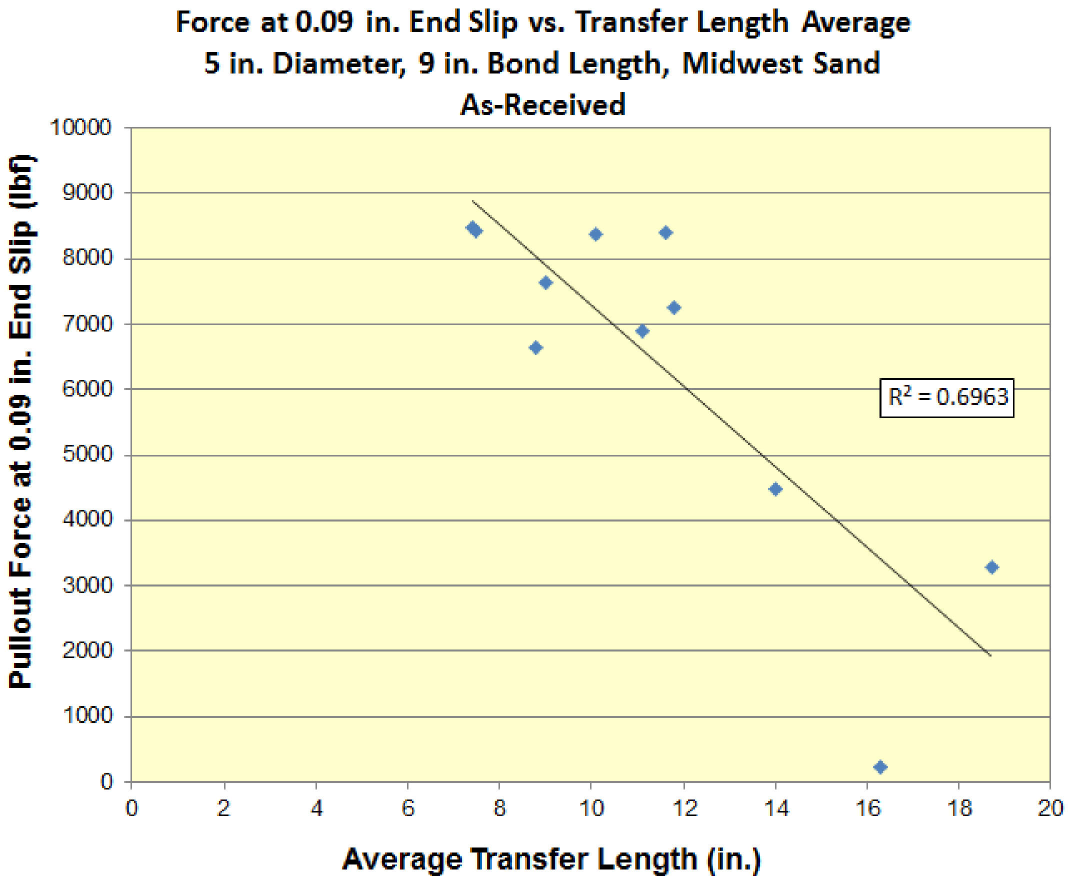


Figure C.9 Test development analysis, pullout force at 0.09 in. end slip (Midwest sand)

Table C.10 Test development analysis, pullout force at 0.10 in. end slip (Midwest sand)

As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Midwest Sand
Pullout Force at 0.10 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	248	27	10.8	16.3
[WB]	8242	95	1.1	11.6
[WC]	7197	1679	23.3	8.8
[WD]	6652	473	7.1	11.1
[WE]	8497	0	0.0	7.4
[WF]				
[WG]	7276	797	10.9	11.8
[WH]	8252	254	3.1	7.5
[WI]	8122	393	4.8	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	4524	310	6.8	14.0
[WL]	3354	351	10.5	18.7

Note: Sample Size = 6, D = 5, E = 1, F = 0, H = 3, J = 5

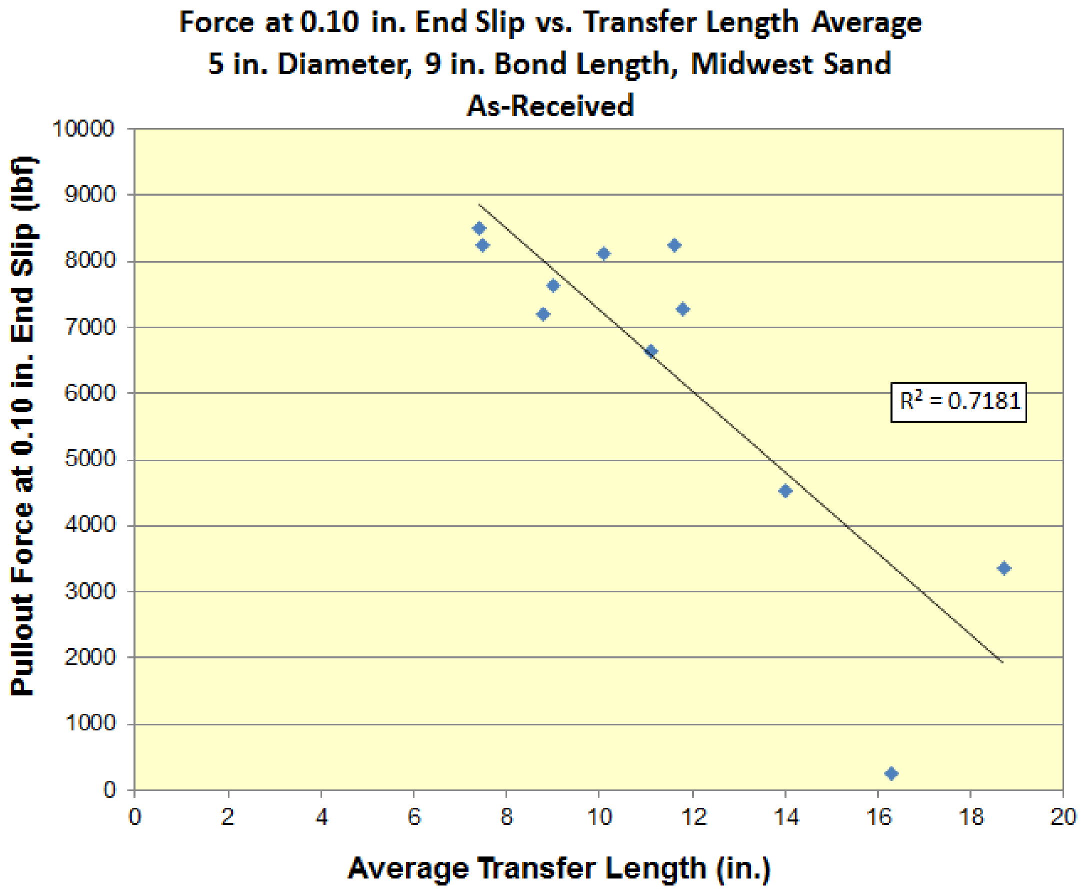
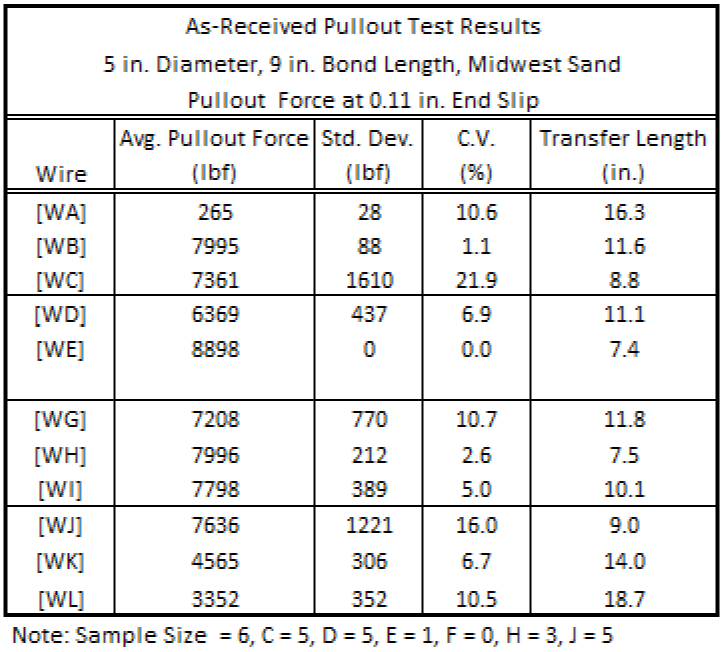


Figure C.10 Test development analysis, pullout force at 0.10 in. end slip (Midwest sand)

Table C.11 Test development analysis, pullout force at 0.11 in. end slip (Midwest sand)



As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Midwest Sand
Pullout Force at 0.11 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	265	28	10.6	16.3
[WB]	7995	88	1.1	11.6
[WC]	7361	1610	21.9	8.8
[WD]	6369	437	6.9	11.1
[WE]	8898	0	0.0	7.4
[WG]	7208	770	10.7	11.8
[WH]	7996	212	2.6	7.5
[WI]	7798	389	5.0	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	4565	306	6.7	14.0
[WL]	3352	352	10.5	18.7

Note: Sample Size = 6, C = 5, D = 5, E = 1, F = 0, H = 3, J = 5

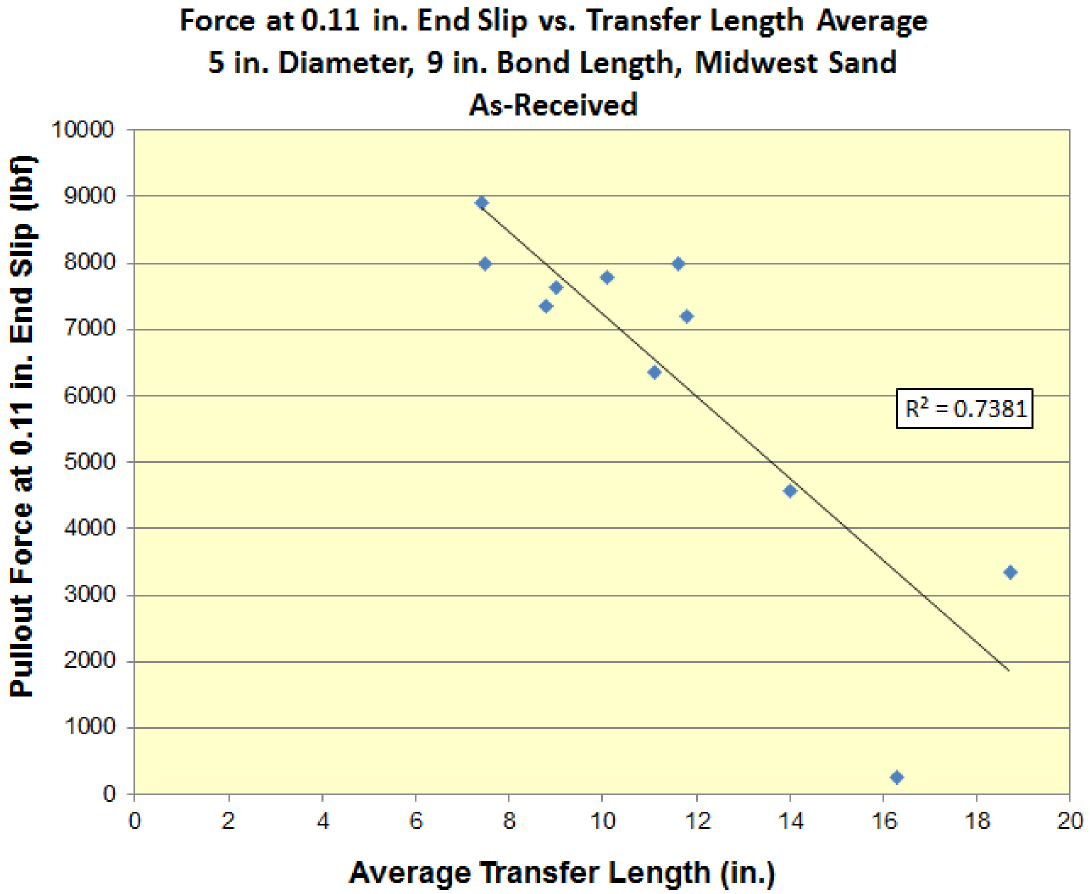
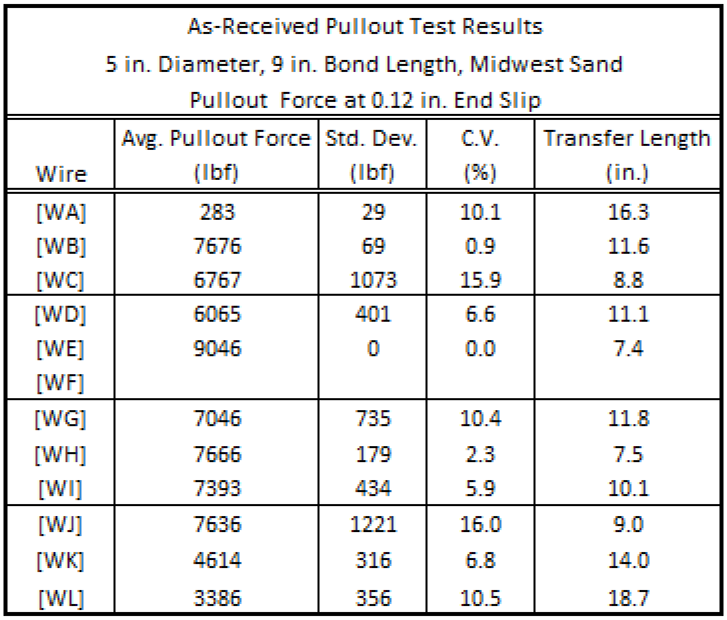


Figure C.11 Test development analysis, pullout force at 0.11 in. end slip (Midwest sand)

Table C.12 Test development analysis, pullout force at 0.12 in. end slip (Midwest sand)



As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Midwest Sand
Pullout Force at 0.12 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	283	29	10.1	16.3
[WB]	7676	69	0.9	11.6
[WC]	6767	1073	15.9	8.8
[WD]	6065	401	6.6	11.1
[WE]	9046	0	0.0	7.4
[WF]				
[WG]	7046	735	10.4	11.8
[WH]	7666	179	2.3	7.5
[WI]	7393	434	5.9	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	4614	316	6.8	14.0
[WL]	3386	356	10.5	18.7

Note: Sample Size = 6, C = 3, D = 5, E = 1, F = 0, H = 3, I = 5, J = 5

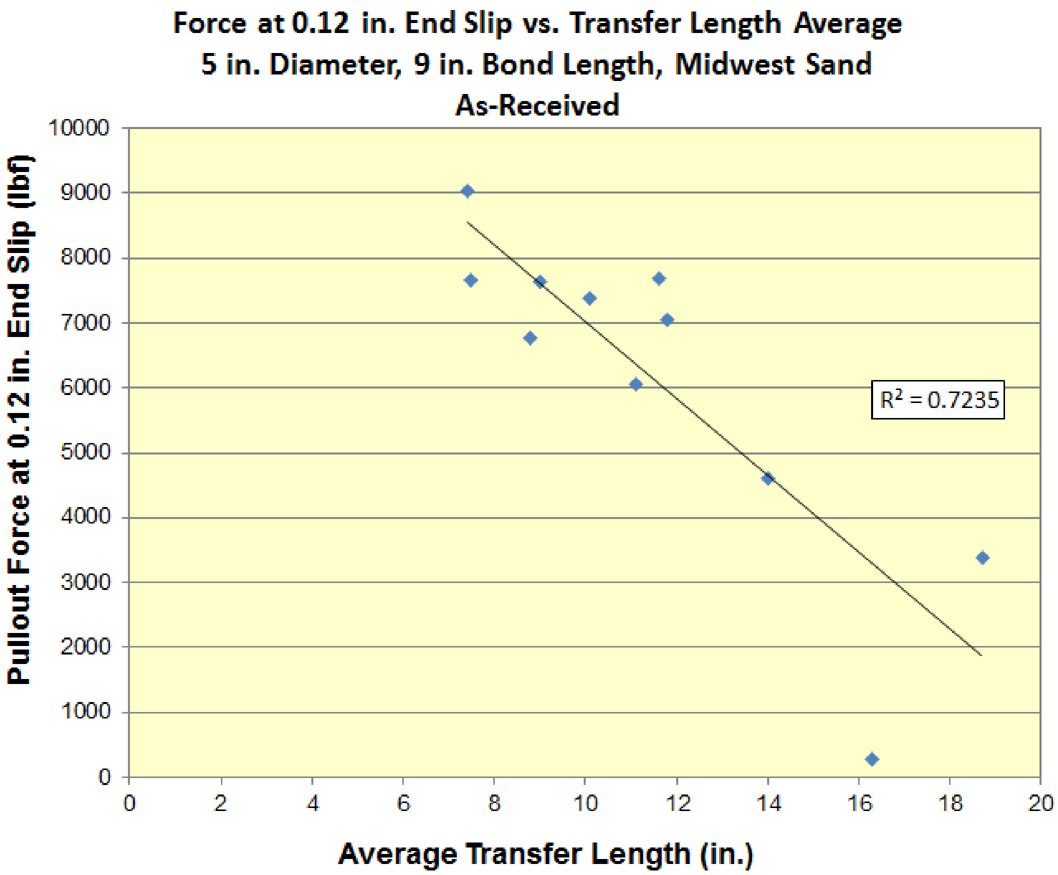


Figure C.12 Test development analysis, pullout force at 0.12 in. end slip (Midwest sand)

Table C.13 Test development analysis, pullout force at 0.13 in. end slip (Midwest sand)

As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Midwest Sand
Pullout Force at 0.13 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	301	29	9.5	16.3
[WB]	7278	52	0.7	11.6
[WC]	7313	1126	15.4	8.8
[WD]	5735	358	6.2	11.1
[WE]				
[WF]				
[WG]	6771	689	10.2	11.8
[WH]	6960	621	8.9	7.5
[WI]	6371	1130	17.7	10.1
[WJ]	7636	1221	16.0	9.0
[WK]	4648	321	6.9	14.0
[WL]	3392	370	10.9	18.7

Note: Sample Size = 6, C = 3, D = 5, E = 0, F = 0, H = 3, I = 5, J = 5

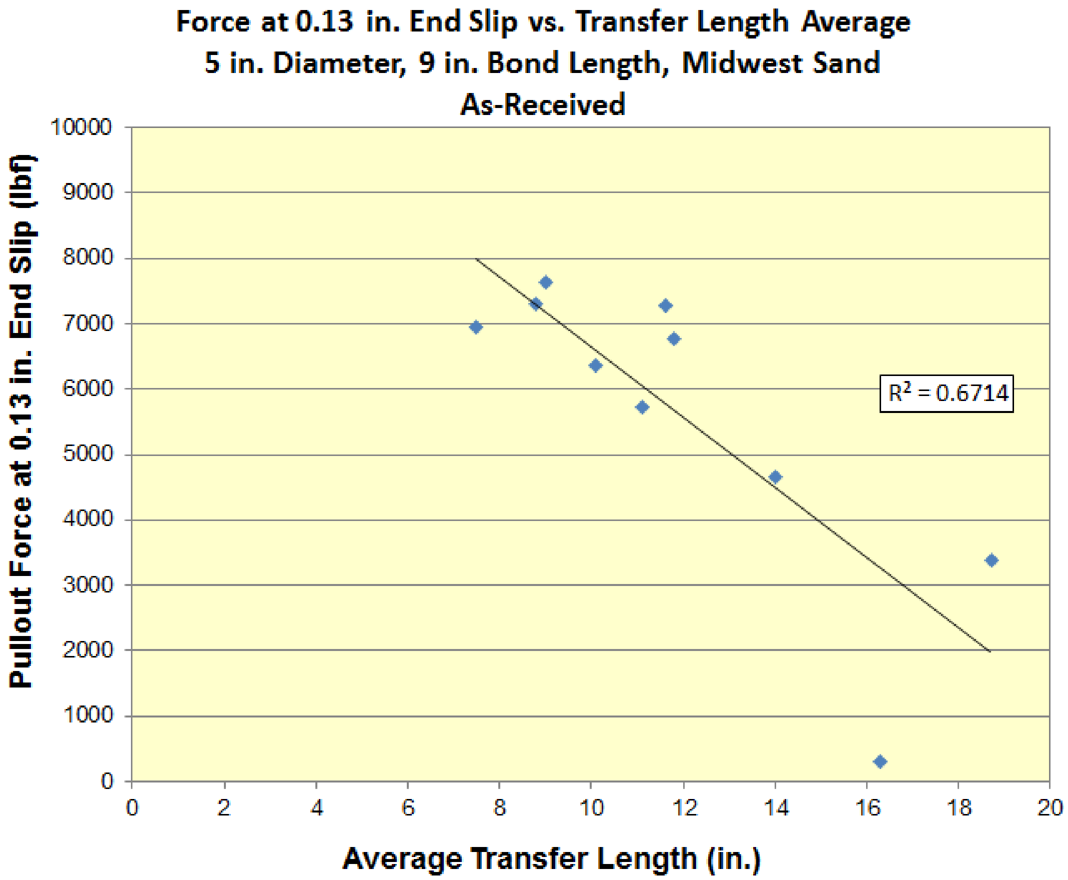


Figure C.13 Test development analysis, pullout force at 0.13 in. end slip (Midwest sand)

Table C.14 Test development analysis, maximum pullout force (Midwest sand)

As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Midwest Sand
Maximum PullOut Force

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	452	65	14.3	16.3
[WB]	8463	114	1.3	11.6
[WC]	7172	1675	23.4	8.8
[WD]	7573	922	12.2	11.1
[WE]	9115	284	3.1	7.4
[WF]	9228	78	0.8	8.5
[WG]	7289	801	11.0	11.8
[WH]	8496	678	8.0	7.5
[WI]	8547	407	4.8	10.1
[WJ]	8973	492	5.5	9.0
[WK]	4557	316	6.9	14.0
[WL]	3362	355	10.6	18.7

Note: Sample Size = 6

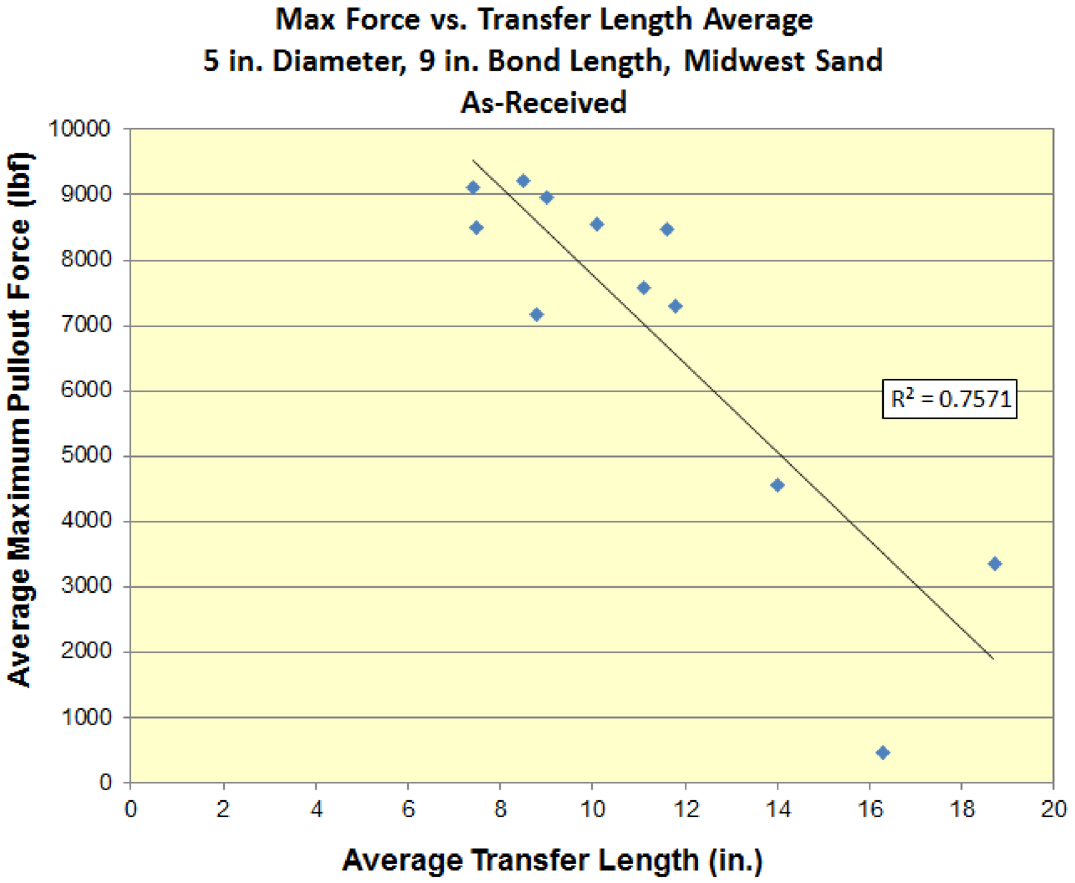


Figure C.14 Test development analysis, maximum pullout force (Midwest sand)

Table C.15 Test development analysis, pullout force at 0.01 in. end slip (Ottawa sand)

As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Ottawa Sand
Pullout Force at 0.01 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	334	83	24.7	16.3
[WB]	3592	2124	59.1	11.6
[WC]	1991	787	39.5	8.8
[WD]	3788	2332	61.6	11.1
[WE]	2135	1040	48.7	7.4
[WF]	5301	3087	58.2	8.5
[WG]	1619	850	52.5	11.8
[WH]	5199	3121	60.0	7.5
[WI]	3353	2096	62.5	10.1
[WJ]	4522	2917	64.5	9.0
[WK]	2058	271	13.1	14.0
[WL]	1064	185	17.4	18.7

Note: Sample Size = 6

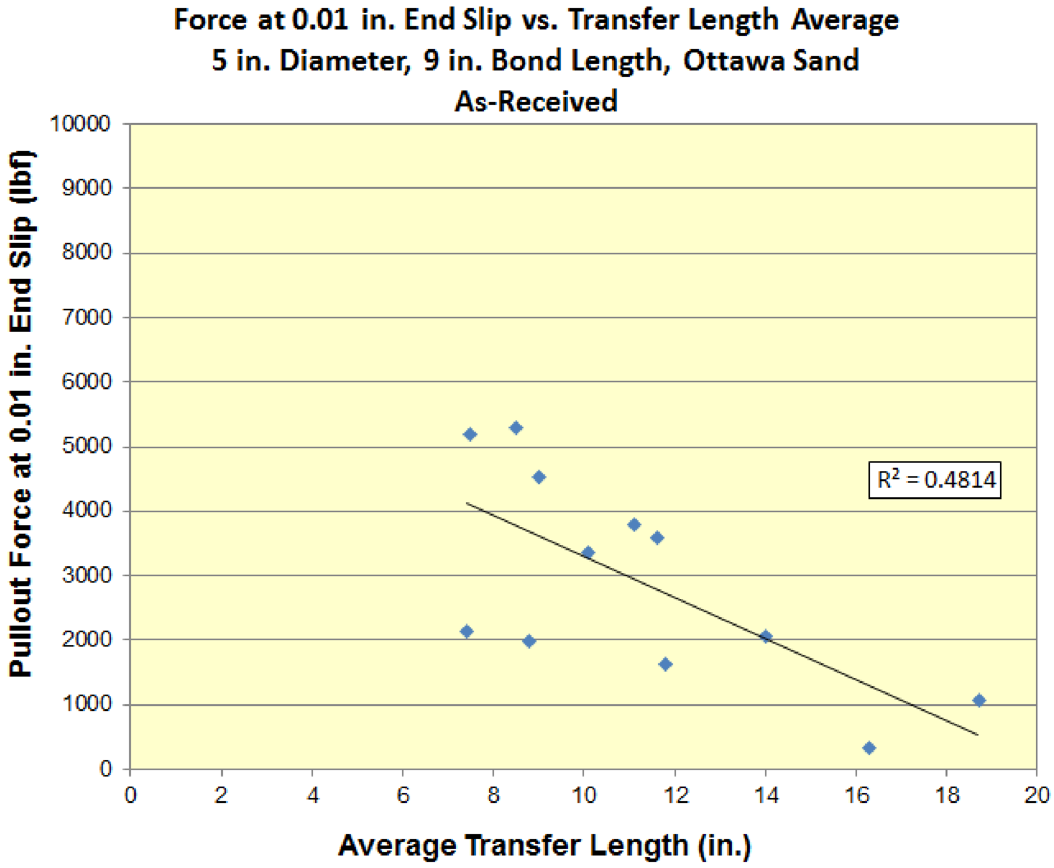


Figure C.15 Test development analysis, pullout force at 0.01 in. end slip (Ottawa sand)

Table C.16 Test development analysis, pullout force at 0.02 in. end slip (Ottawa sand)

As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Ottawa Sand
Pullout Force at 0.02 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	299	71	23.8	16.3
[WB]	5688	2139	37.6	11.6
[WC]	3595	1471	40.9	8.8
[WD]	5865	4032	68.8	11.1
[WE]	4056	1732	42.7	7.4
[WF]	5276	5315	100.7	8.5
[WG]	3119	1469	47.1	11.8
[WH]	5518	2322	42.1	7.5
[WI]	5573	2887	51.8	10.1
[WJ]	5206	3379	64.9	9.0
[WK]	3474	229	6.6	14.0
[WL]	1937	216	11.2	18.7

Note: Sample Size = 6, D = 5, F = 3, H = 3, J = 4

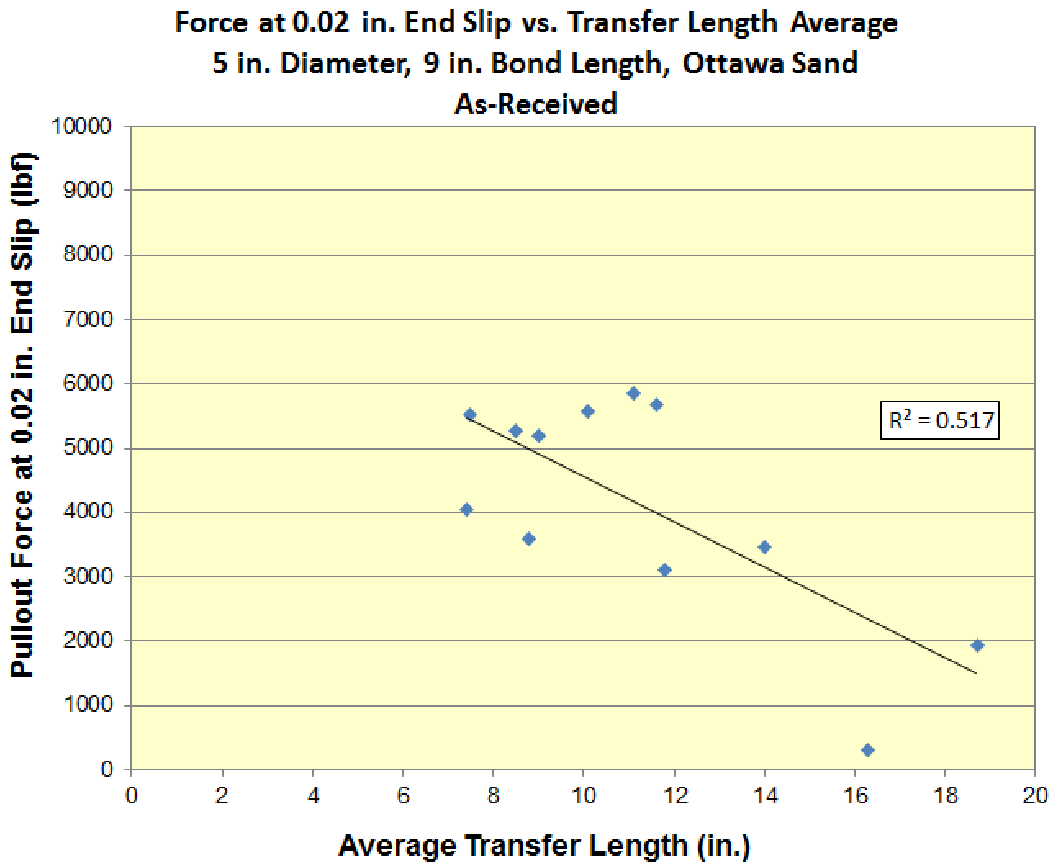


Figure C.16 Test development analysis, pullout force at 0.02 in. end slip (Ottawa sand)

Table C.17 Test development analysis, pullout force at 0.03 in. end slip (Ottawa sand)

As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Ottawa Sand
Pullout Force at 0.03 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	296	67	22.6	16.3
[WB]	7012	1481	21.1	11.6
[WC]	4910	1681	34.2	8.8
[WD]	5603	4342	77.5	11.1
[WE]	5550	1968	35.5	7.4
[WF]	6218	267	4.3	8.5
[WG]	4407	1498	34.0	11.8
[WH]	6384	441	6.9	7.5
[WI]	6679	2525	37.8	10.1
[WJ]	4484	648	14.5	9.0
[WK]	4290	231	5.4	14.0
[WL]	2546	230	9.0	18.7

Note: Sample Size = 6, D = 3, F = 2, H = 2, I = 5, J = 2

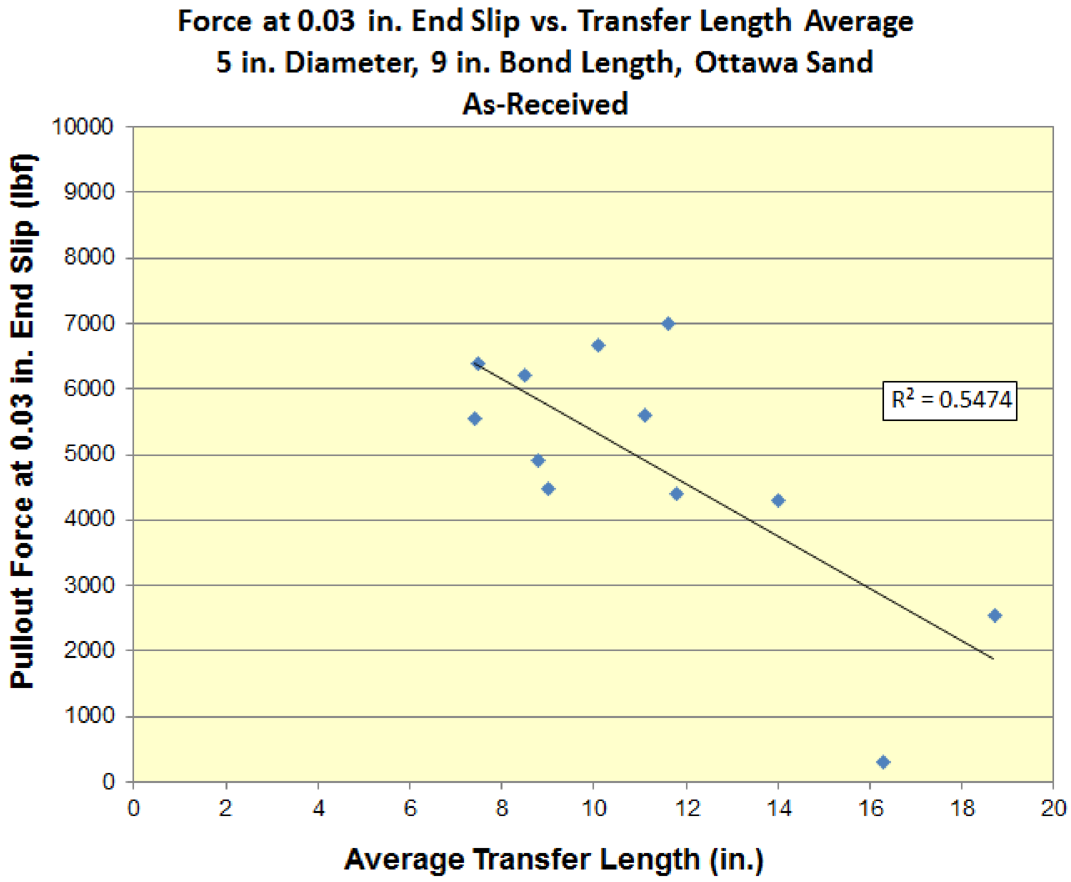


Figure C.17 Test development analysis, pullout force at 0.03 in. end slip (Ottawa sand)

Table C.18 Test development analysis, pullout force at 0.04 in. end slip (Ottawa sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Ottawa Sand Pullout Force at 0.04 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	307	69	22.5	16.3
[WB]	7621	1039	13.6	11.6
[WC]	5307	806	15.2	8.8
[WD]	6599	1226	18.6	11.1
[WE]	6688	1975	29.5	7.4
[WF]	7876	308	3.9	8.5
[WG]	5457	1323	24.2	11.8
[WH]	7667	449	5.9	7.5
[WI]	6641	1633	24.6	10.1
[WJ]	6392	650	10.2	9.0
[WK]	4717	264	5.6	14.0
[WL]	2983	255	8.5	18.7

Note: Sample Size = 6, C = 5, D = 3, F = 2, H = 2, I = 3, J = 2

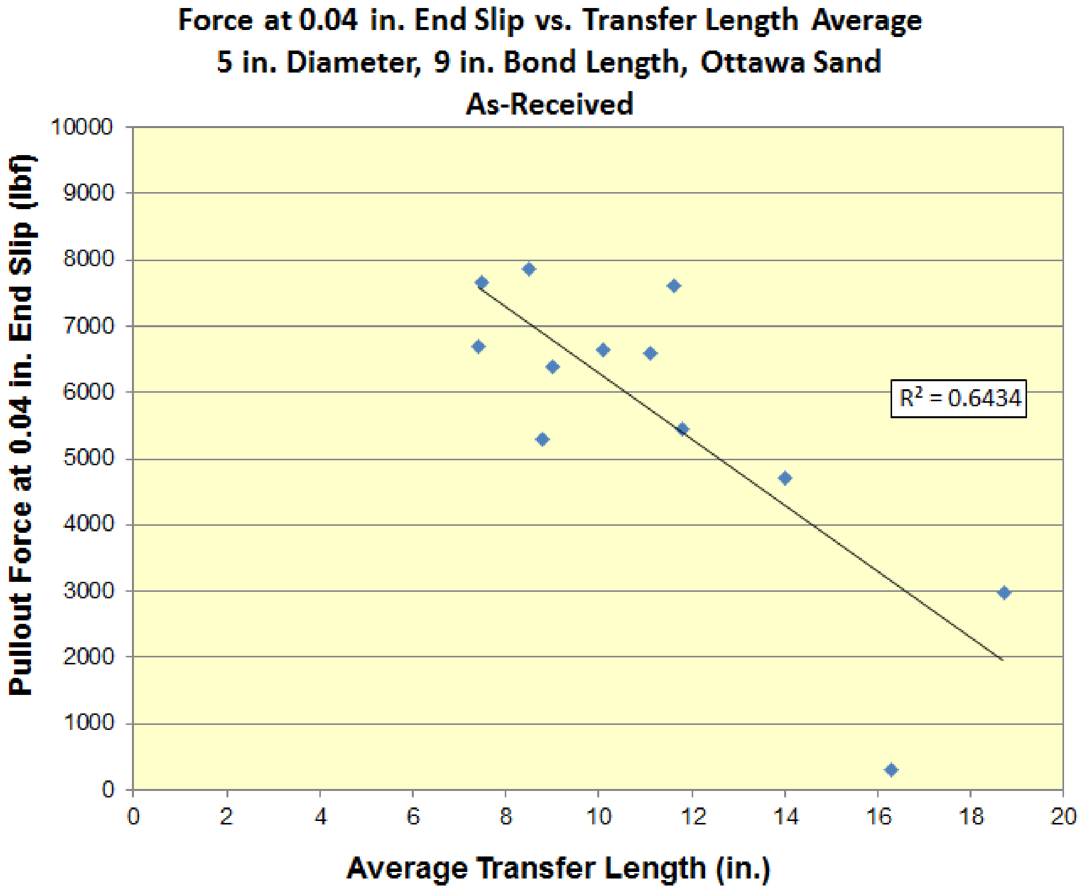
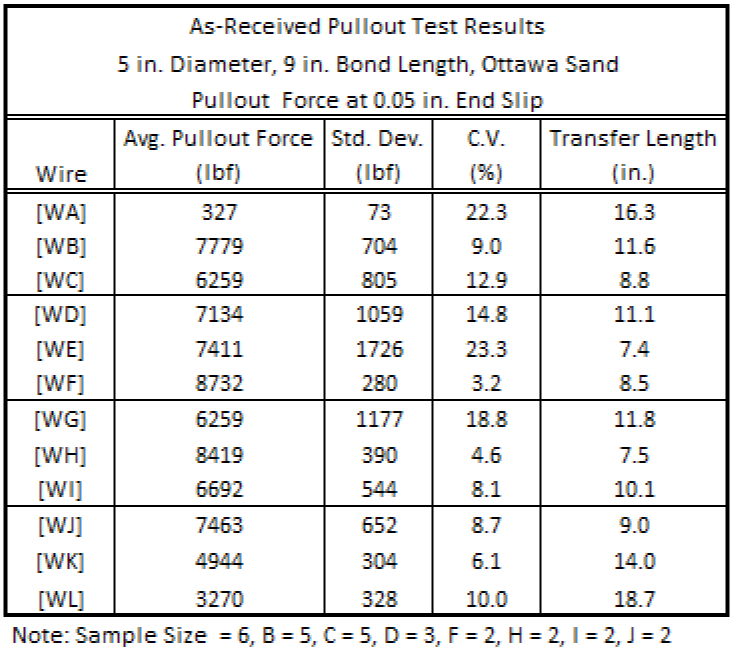


Figure C.18 Test development analysis, pullout force at 0.04 in. end slip (Ottawa sand)

Table C.19 Test development analysis, pullout force at 0.05 in. end slip (Ottawa sand)



As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Ottawa Sand
Pullout Force at 0.05 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	327	73	22.3	16.3
[WB]	7779	704	9.0	11.6
[WC]	6259	805	12.9	8.8
[WD]	7134	1059	14.8	11.1
[WE]	7411	1726	23.3	7.4
[WF]	8732	280	3.2	8.5
[WG]	6259	1177	18.8	11.8
[WH]	8419	390	4.6	7.5
[WI]	6692	544	8.1	10.1
[WJ]	7463	652	8.7	9.0
[WK]	4944	304	6.1	14.0
[WL]	3270	328	10.0	18.7

Note: Sample Size = 6, B = 5, C = 5, D = 3, F = 2, H = 2, I = 2, J = 2

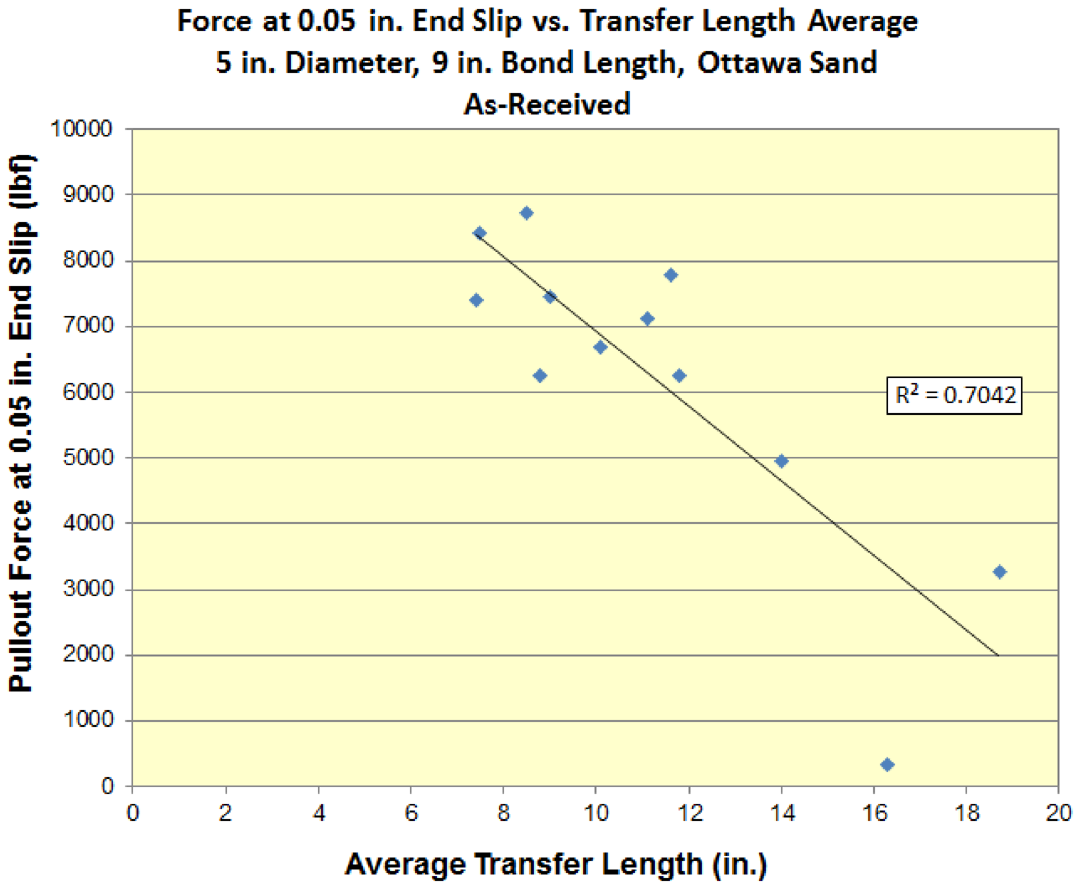
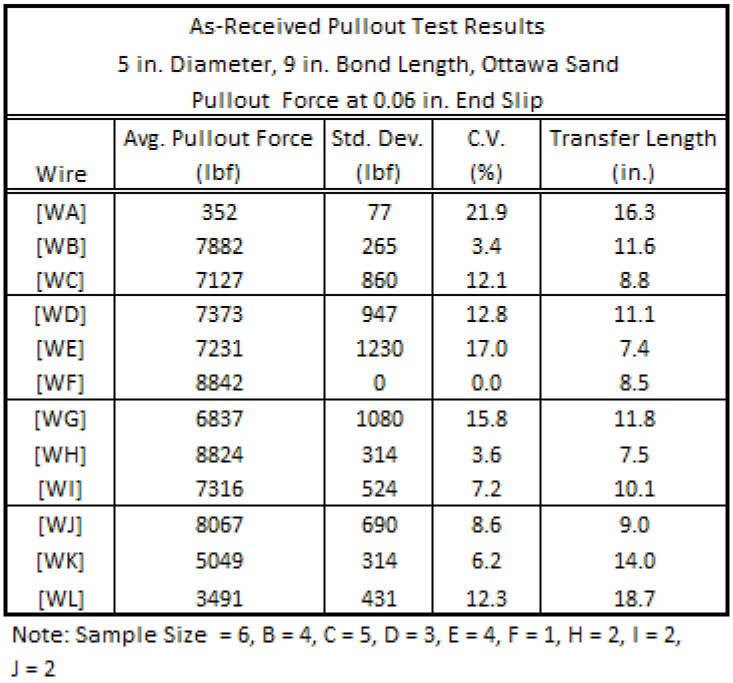


Figure C.19 Test development analysis, pullout force at 0.05 in. end slip (Ottawa sand)

Table C.20 Test development analysis, pullout force at 0.06 in. end slip (Ottawa sand)



As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Ottawa Sand
Pullout Force at 0.06 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	352	77	21.9	16.3
[WB]	7882	265	3.4	11.6
[WC]	7127	860	12.1	8.8
[WD]	7373	947	12.8	11.1
[WE]	7231	1230	17.0	7.4
[WF]	8842	0	0.0	8.5
[WG]	6837	1080	15.8	11.8
[WH]	8824	314	3.6	7.5
[WI]	7316	524	7.2	10.1
[WJ]	8067	690	8.6	9.0
[WK]	5049	314	6.2	14.0
[WL]	3491	431	12.3	18.7

Note: Sample Size = 6, B = 4, C = 5, D = 3, E = 4, F = 1, H = 2, I = 2, J = 2

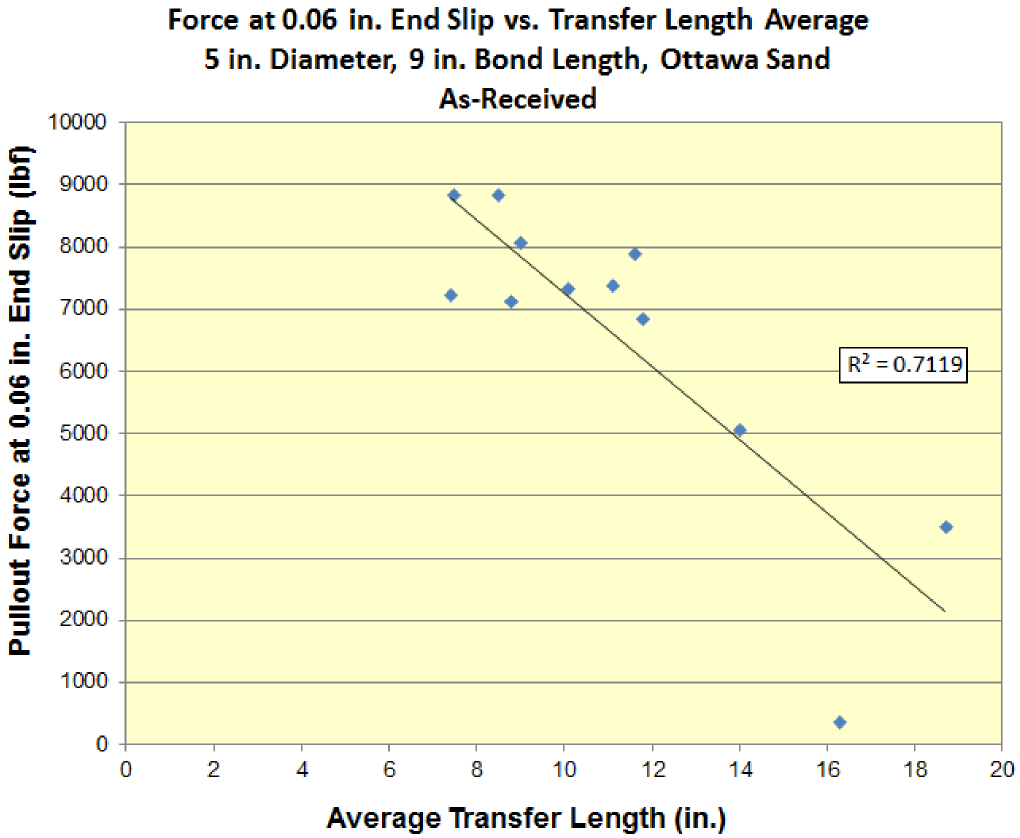


Figure C.20 Test development analysis, pullout force at 0.06 in. end slip (Ottawa sand)

Table C.21 Test development analysis, pullout force at 0.07 in. end slip (Ottawa sand)

As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Ottawa Sand
Pullout Force at 0.07 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	380	81	21.4	16.3
[WB]	8139	203	2.5	11.6
[WC]	7909	898	11.4	8.8
[WD]	7437	871	11.7	11.1
[WE]	7273	556	7.6	7.4
[WF]	9008	0	0.0	8.5
[WG]	7016	1010	14.4	11.8
[WH]	8750	0	0.0	7.5
[WI]	7671	490	6.4	10.1
[WJ]	8372	716	8.5	9.0
[WK]	5130	354	6.9	14.0
[WL]	3657	486	13.3	18.7

Note: Sample Size = 6, B = 4, C = 5, D = 3, E = 3, F = 1, G = 5, H = 1,
I = 2, J = 2

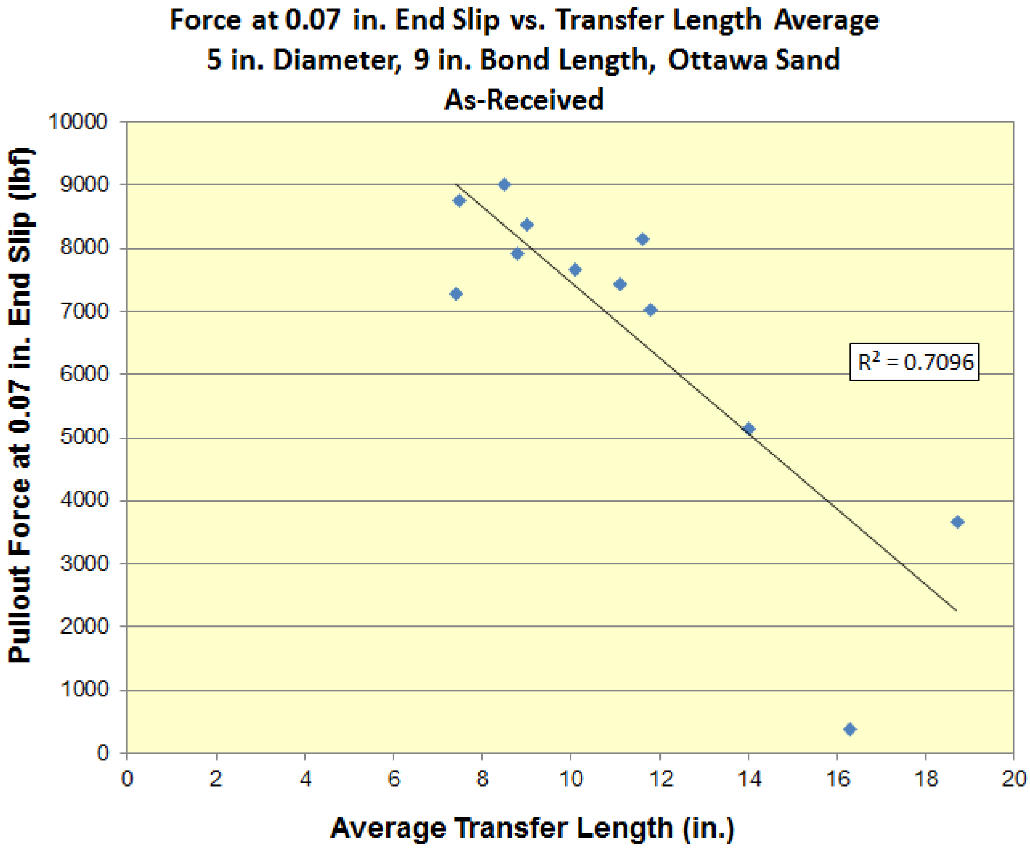


Figure C.21 Test development analysis, pullout force at 0.07 in. end slip (Ottawa sand)

Table C.22 Test development analysis, pullout force at 0.08 in. end slip (Ottawa sand)

As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Ottawa Sand
Pullout Force at 0.08 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	406	84	20.8	16.3
[WB]	8282	195	2.4	11.6
[WC]	8026	412	5.1	8.8
[WD]	7402	803	10.8	11.1
[WE]	7885	485	6.2	7.4
[WF]	9046	0	0.0	8.5
[WG]	7240	958	13.2	11.8
[WH]	8865	0	0.0	7.5
[WI]	7875	443	5.6	10.1
[WJ]	7789	0	0.0	9.0
[WK]	5162	375	7.3	14.0
[WL]	3755	524	13.9	18.7

Note: Sample Size = 6, B = 4, C = 3, D = 3, E = 3, F = 1, G = 5, H = 1, I = 2, J = 1

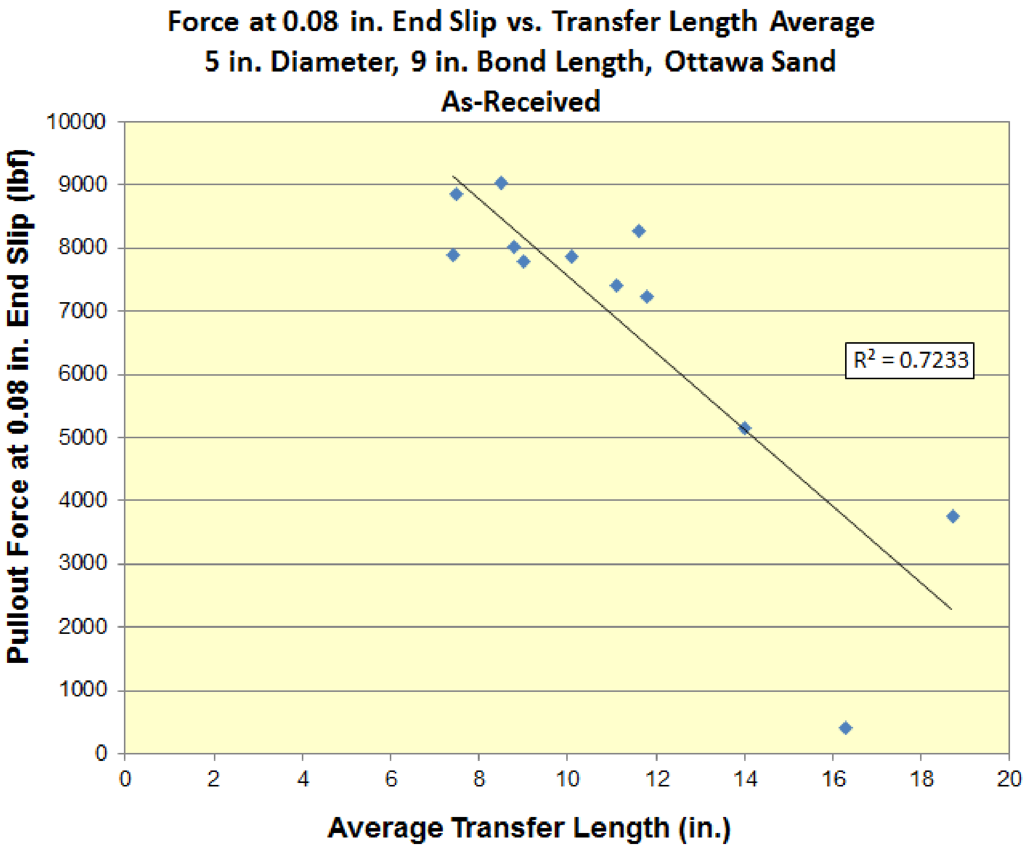
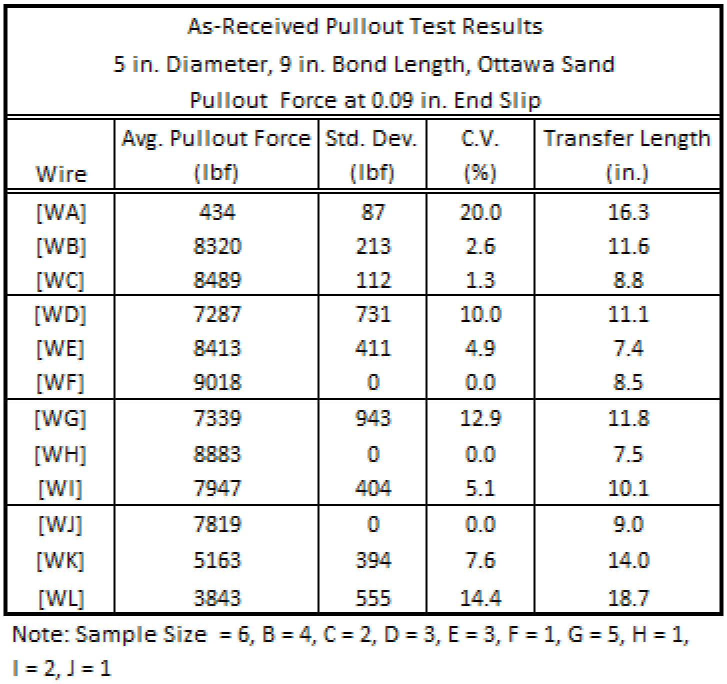


Figure C.22 Test development analysis, pullout force at 0.08 in. end slip (Ottawa sand)

Table C.23 Test development analysis, pullout force at 0.09 in. end slip (Ottawa sand)



As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Ottawa Sand
Pullout Force at 0.09 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	434	87	20.0	16.3
[WB]	8320	213	2.6	11.6
[WC]	8489	112	1.3	8.8
[WD]	7287	731	10.0	11.1
[WE]	8413	411	4.9	7.4
[WF]	9018	0	0.0	8.5
[WG]	7339	943	12.9	11.8
[WH]	8883	0	0.0	7.5
[WI]	7947	404	5.1	10.1
[WJ]	7819	0	0.0	9.0
[WK]	5163	394	7.6	14.0
[WL]	3843	555	14.4	18.7

Note: Sample Size = 6, B = 4, C = 2, D = 3, E = 3, F = 1, G = 5, H = 1,
I = 2, J = 1

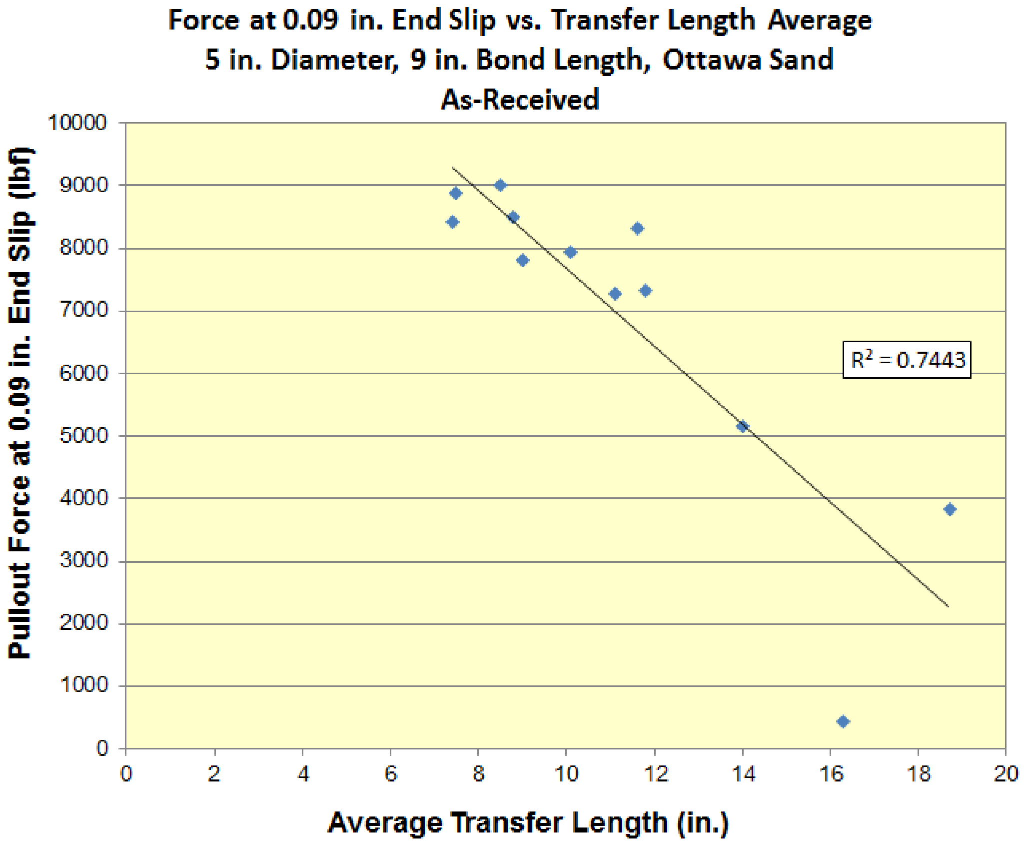
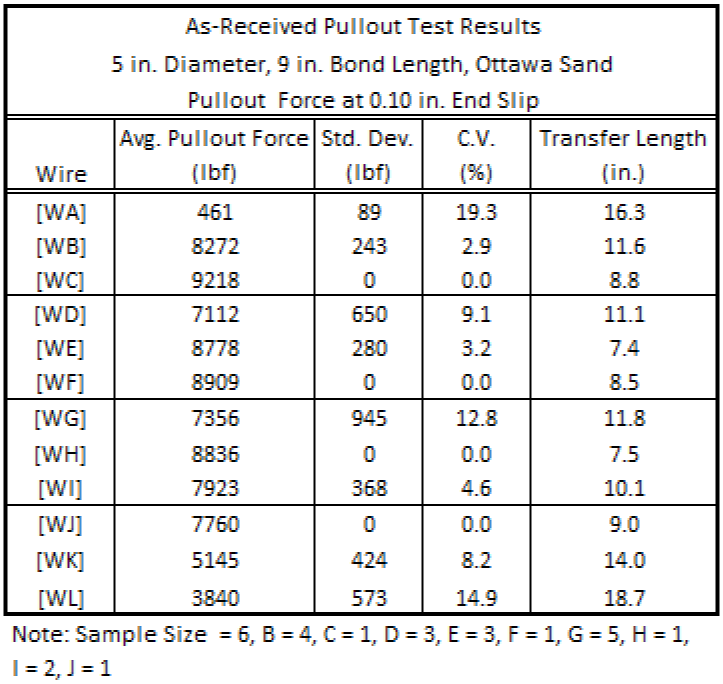


Figure C.23 Test development analysis, pullout force at 0.09 in. end slip (Ottawa sand)

Table C.24 Test development analysis, pullout force at 0.10 in. end slip (Ottawa sand)



As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Ottawa Sand
Pullout Force at 0.10 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	461	89	19.3	16.3
[WB]	8272	243	2.9	11.6
[WC]	9218	0	0.0	8.8
[WD]	7112	650	9.1	11.1
[WE]	8778	280	3.2	7.4
[WF]	8909	0	0.0	8.5
[WG]	7356	945	12.8	11.8
[WH]	8836	0	0.0	7.5
[WI]	7923	368	4.6	10.1
[WJ]	7760	0	0.0	9.0
[WK]	5145	424	8.2	14.0
[WL]	3840	573	14.9	18.7

Note: Sample Size = 6, B = 4, C = 1, D = 3, E = 3, F = 1, G = 5, H = 1, I = 2, J = 1

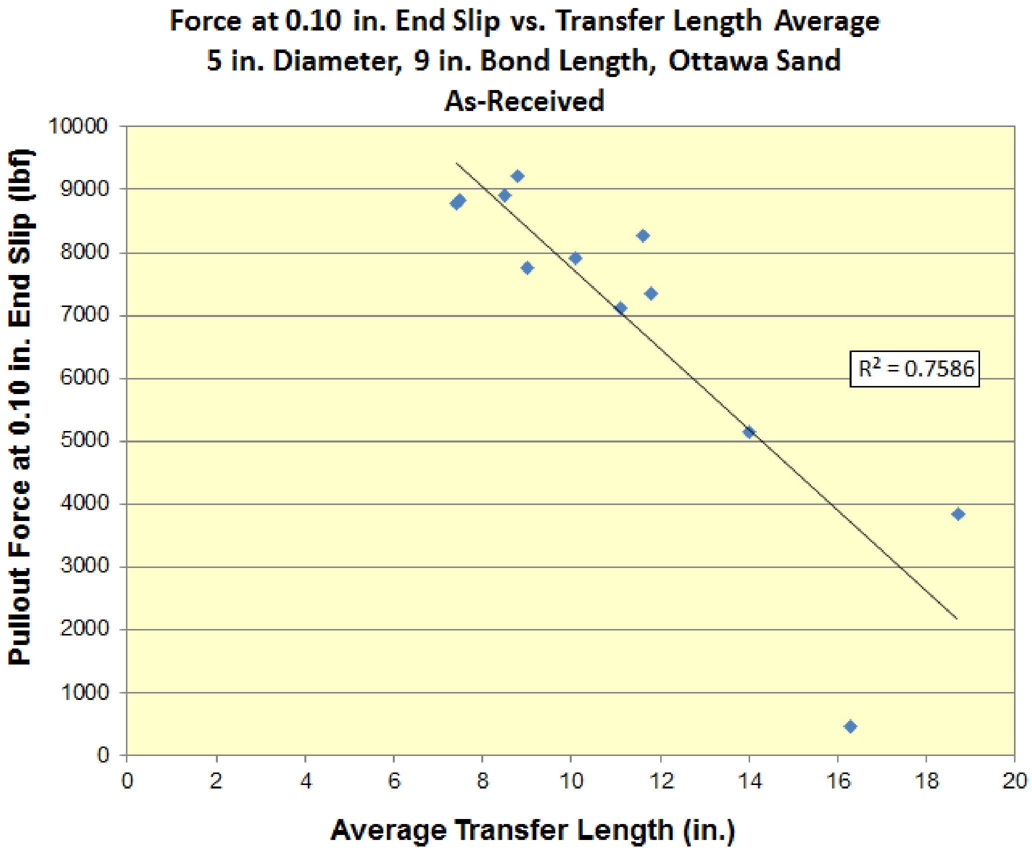
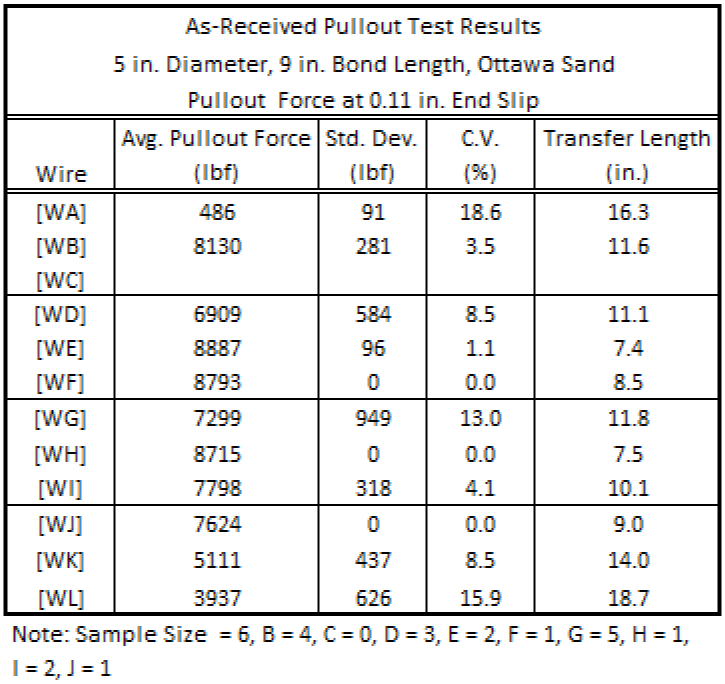


Figure C.24 Test development analysis, pullout force at 0.10 in. end slip (Ottawa sand)

Table C.25 Test development analysis, pullout force at 0.11 in. end slip (Ottawa sand)



As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Ottawa Sand
Pullout Force at 0.11 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	486	91	18.6	16.3
[WB]	8130	281	3.5	11.6
[WC]				
[WD]	6909	584	8.5	11.1
[WE]	8887	96	1.1	7.4
[WF]	8793	0	0.0	8.5
[WG]	7299	949	13.0	11.8
[WH]	8715	0	0.0	7.5
[WI]	7798	318	4.1	10.1
[WJ]	7624	0	0.0	9.0
[WK]	5111	437	8.5	14.0
[WL]	3937	626	15.9	18.7

Note: Sample Size = 6, B = 4, C = 0, D = 3, E = 2, F = 1, G = 5, H = 1, I = 2, J = 1

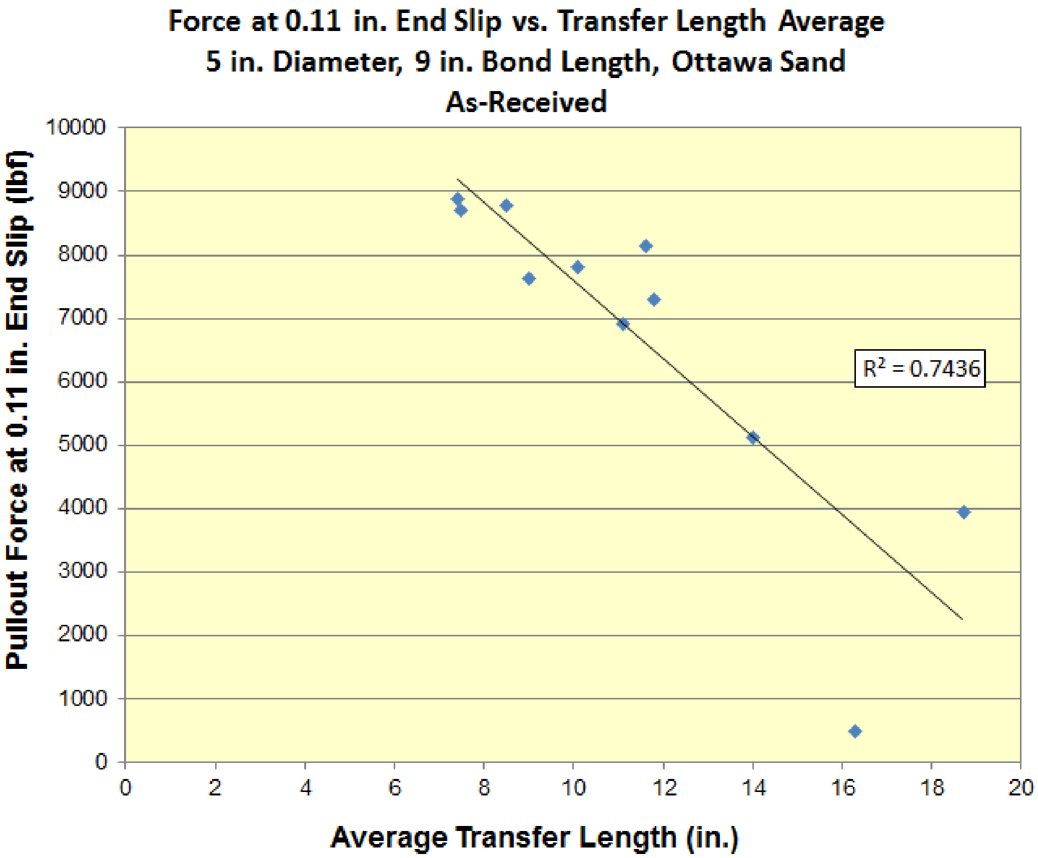
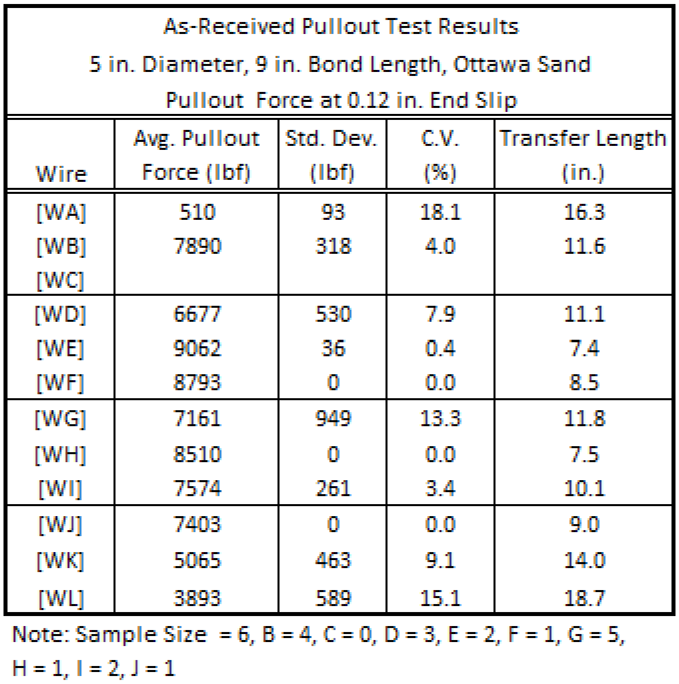


Figure C.25 Test development analysis, pullout force at 0.11 in. end slip (Ottawa sand)

Table C.26 Test development analysis, pullout force at 0.12 in. end slip (Ottawa sand)



As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Ottawa Sand
Pullout Force at 0.12 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	510	93	18.1	16.3
[WB]	7890	318	4.0	11.6
[WC]				
[WD]	6677	530	7.9	11.1
[WE]	9062	36	0.4	7.4
[WF]	8793	0	0.0	8.5
[WG]	7161	949	13.3	11.8
[WH]	8510	0	0.0	7.5
[WI]	7574	261	3.4	10.1
[WJ]	7403	0	0.0	9.0
[WK]	5065	463	9.1	14.0
[WL]	3893	589	15.1	18.7

Note: Sample Size = 6, B = 4, C = 0, D = 3, E = 2, F = 1, G = 5,
H = 1, I = 2, J = 1

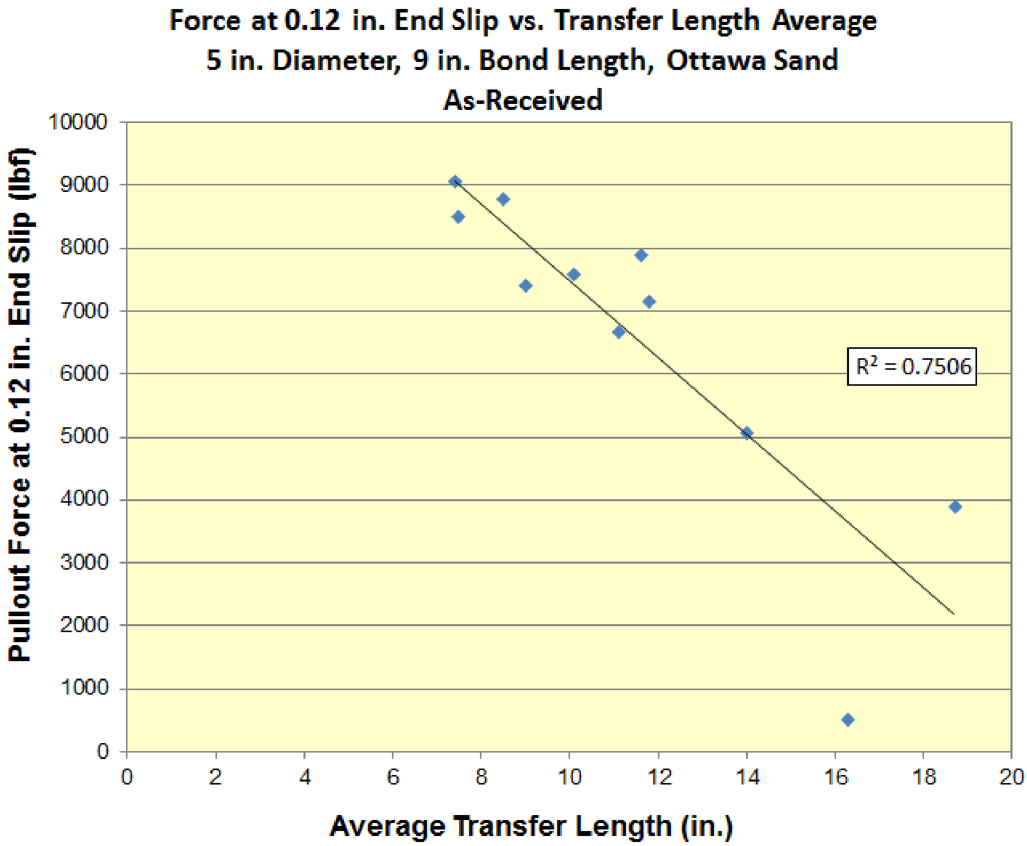


Figure C.26 Test development analysis, pullout force at 0.12 in. end slip (Ottawa sand)

Table C.27 Test development analysis, pullout force at 0.13 in. end slip (Ottawa sand)

As-Received Pullout Test Results 5 in. Diameter, 9 in. Bond Length, Ottawa Sand Pullout Force at 0.13 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	517	95	18.4	16.3
[WB]	7578	343	4.5	11.6
[WC]				
[WD]	6409	464	7.2	11.1
[WE]	9201	3	0.0	7.4
[WF]	8793	0	0.0	8.5
[WG]	6912	941	13.6	11.8
[WH]	8206	0	0.0	7.5
[WI]	7217	209	2.9	10.1
[WJ]	7133	0	0.0	9.0
[WK]	5031	488	9.7	14.0
[WL]	3851	566	14.7	18.7

Note: Sample Size = 6, A = 5, B = 4, C = 0, D = 3, E = 2, F = 1, G = 5, H = 1, I = 2, J = 1

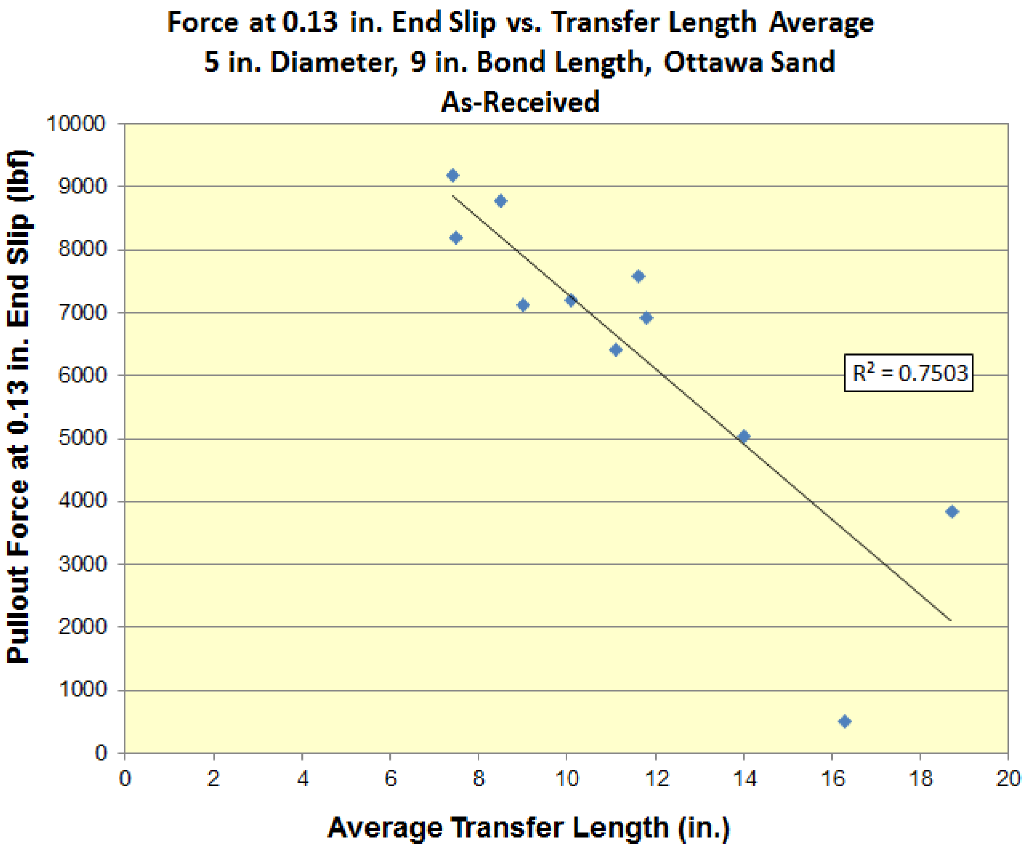


Figure C.27Test development analysis, pullout force at 0.13 in. end slip (Ottawa sand)

Table C.28 Test development analysis, maximum pullout force (Ottawa sand)

As-Received Pullout Test Results
5 in. Diameter, 9 in. Bond Length, Ottawa Sand
Maximum Pullout Force

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	516	99	19.1	16.3
[WB]	8624	453	5.3	11.6
[WC]	9063	198	2.2	8.8
[WD]	8314	1045	12.6	11.1
[WE]	8987	301	3.4	7.4
[WF]	9168	56	0.6	8.5
[WG]	7482	900	12.0	11.8
[WH]	9119	105	1.2	7.5
[WI]	8770	618	7.1	10.1
[WJ]	8949	506	5.6	9.0
[WK]	5195	396	7.6	14.0
[WL]	3799	480	12.6	18.7

Note: Sample Size = 6

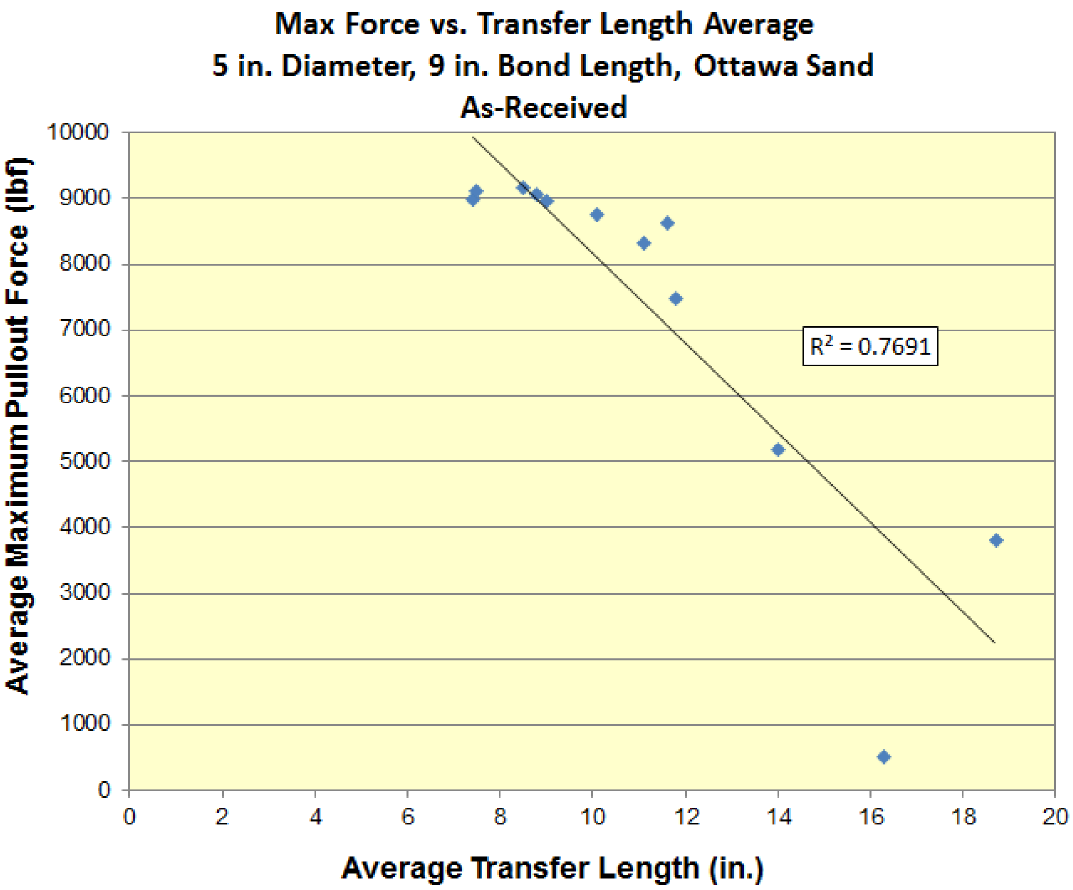
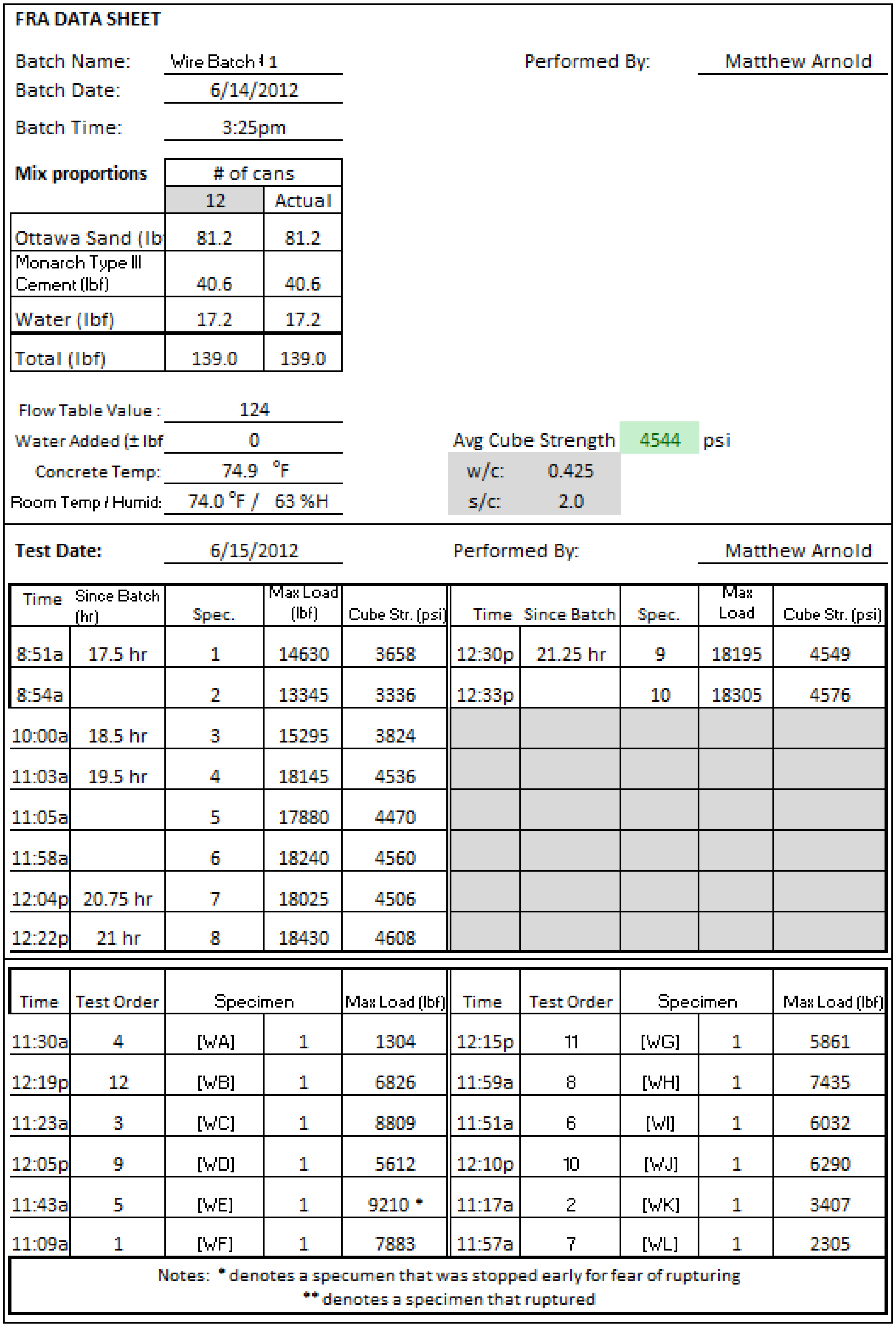


Figure C.28 Test development analysis, maximum pullout force (Ottawa sand)

Appendix D - Lab Phase, Wire; As-Received and Cleaned Batch Summaries



FRA DATA SHEET

Batch Name: Wire Batch # 1
Batch Date: 6/14/2012
Batch Time: 3:25pm

Performed By: Matthew Arnold

Mix proportions	# of cans	
	12	Actual
Ottawa Sand (lb	81.2	81.2
Monarch Type III Cement (lbf)	40.6	40.6
Water (lbf)	17.2	17.2
Total (lbf)	139.0	139.0

Flow Table Value : 124
Water Added (± lbf 0
Concrete Temp: 74.9 °F
Room Temp / Humid: 74.0 °F / 63 %H

Avg Cube Strength 4544 psi
w/c: 0.425
s/c: 2.0

Test Date: 6/15/2012

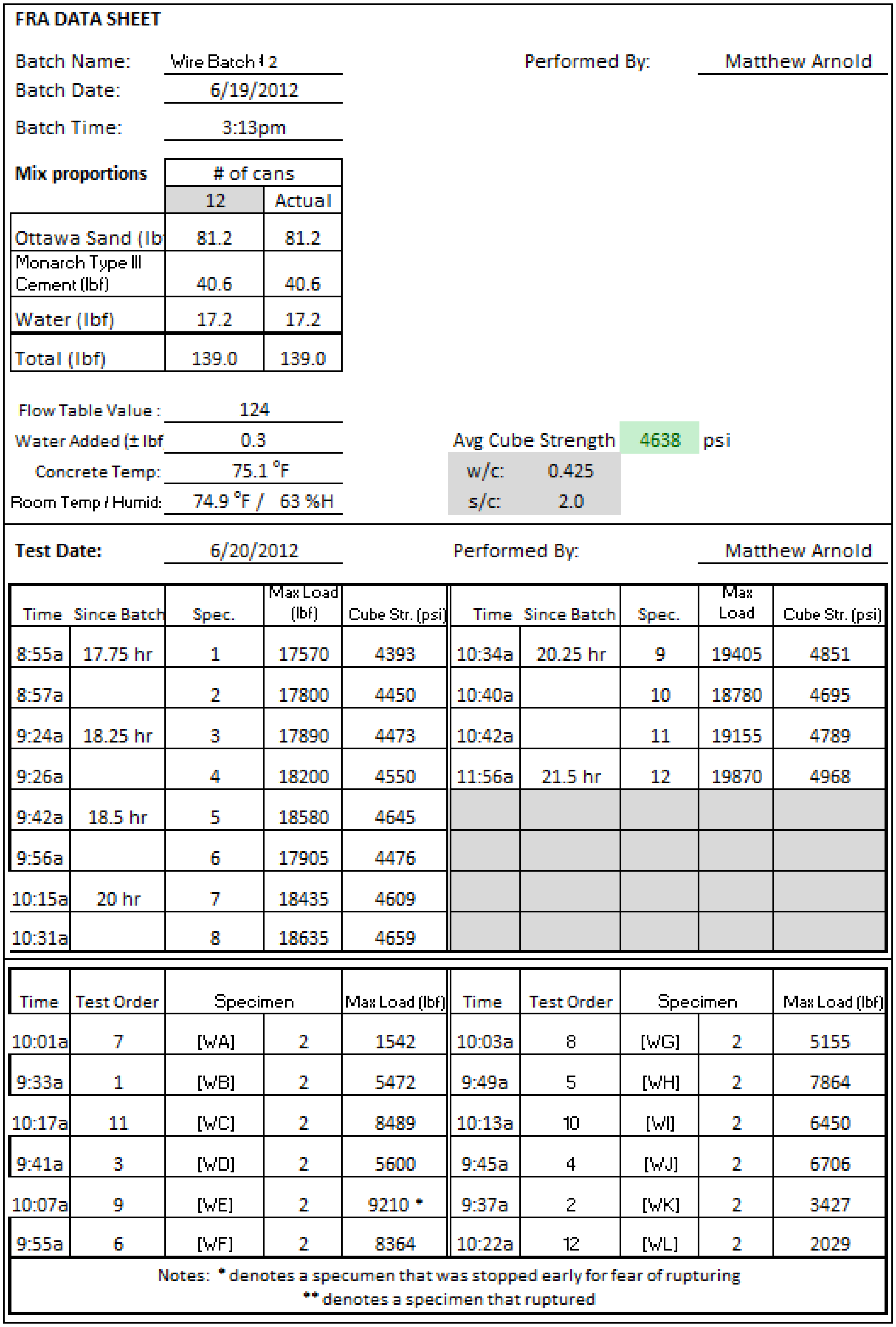
Performed By: Matthew Arnold

Time	Since Batch (hr)	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:51a	17.5 hr	1	14630	3658	12:30p	21.25 hr	9	18195	4549
8:54a		2	13345	3336	12:33p		10	18305	4576
10:00a	18.5 hr	3	15295	3824					
11:03a	19.5 hr	4	18145	4536					
11:05a		5	17880	4470					
11:58a		6	18240	4560					
12:04p	20.75 hr	7	18025	4506					
12:22p	21 hr	8	18430	4608					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
11:30a	4	[WA]	1	1304	12:15p	11	[WG]	1	5861
12:19p	12	[WB]	1	6826	11:59a	8	[WH]	1	7435
11:23a	3	[WC]	1	8809	11:51a	6	[WI]	1	6032
12:05p	9	[WD]	1	5612	12:10p	10	[WJ]	1	6290
11:43a	5	[WE]	1	9210 *	11:17a	2	[WK]	1	3407
11:09a	1	[WF]	1	7883	11:57a	7	[WL]	1	2305

Notes: * denotes a specumen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure D.1 As-received wires, batch summary #1 (Ottawa sand)



FRA DATA SHEET

Batch Name: Wire Batch # 2
Batch Date: 6/19/2012
Batch Time: 3:13pm

Performed By: Matthew Arnold

Mix proportions	# of cans	
	12	Actual
Ottawa Sand (lb	81.2	81.2
Monarch Type III Cement (lbf)	40.6	40.6
Water (lbf)	17.2	17.2
Total (lbf)	139.0	139.0

Flow Table Value : 124
Water Added (± lbf 0.3
Concrete Temp: 75.1 °F
Room Temp / Humid: 74.9 °F / 63 %H

Avg Cube Strength	4638	psi
w/c:	0.425	
s/c:	2.0	

Test Date: 6/20/2012

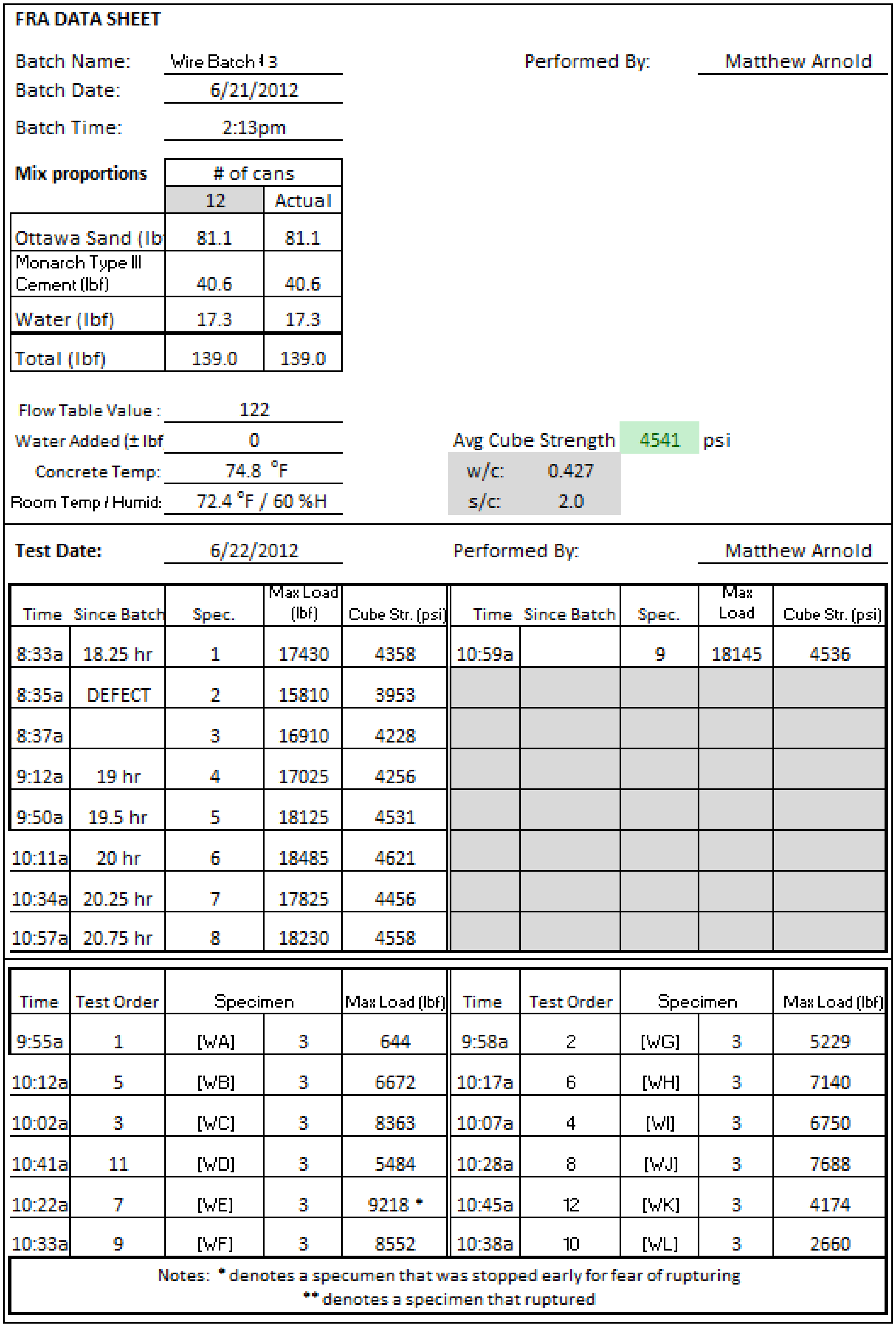
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:55a	17.75 hr	1	17570	4393	10:34a	20.25 hr	9	19405	4851
8:57a		2	17800	4450	10:40a		10	18780	4695
9:24a	18.25 hr	3	17890	4473	10:42a		11	19155	4789
9:26a		4	18200	4550	11:56a	21.5 hr	12	19870	4968
9:42a	18.5 hr	5	18580	4645					
9:56a		6	17905	4476					
10:15a	20 hr	7	18435	4609					
10:31a		8	18635	4659					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
10:01a	7	[WA]	2	1542	10:03a	8	[WG]	2	5155
9:33a	1	[WB]	2	5472	9:49a	5	[WH]	2	7864
10:17a	11	[WC]	2	8489	10:13a	10	[WI]	2	6450
9:41a	3	[WD]	2	5600	9:45a	4	[WJ]	2	6706
10:07a	9	[WE]	2	9210 *	9:37a	2	[WK]	2	3427
9:55a	6	[WF]	2	8364	10:22a	12	[WL]	2	2029

Notes: * denotes a specumen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure D.2 As-received wires, batch summary #2 (Ottawa sand)



FRA DATA SHEET

Batch Name: Wire Batch # 3
Batch Date: 6/21/2012
Batch Time: 2:13pm
Performed By: Matthew Arnold

Mix proportions	# of cans	
	12	Actual
Ottawa Sand (lb	81.1	81.1
Monarch Type III Cement (lbf)	40.6	40.6
Water (lbf)	17.3	17.3
Total (lbf)	139.0	139.0

Flow Table Value : 122
Water Added (± lbf 0
Concrete Temp: 74.8 °F
Room Temp / Humid: 72.4 °F / 60 %H

Avg Cube Strength 4541 psi
w/c: 0.427
s/c: 2.0

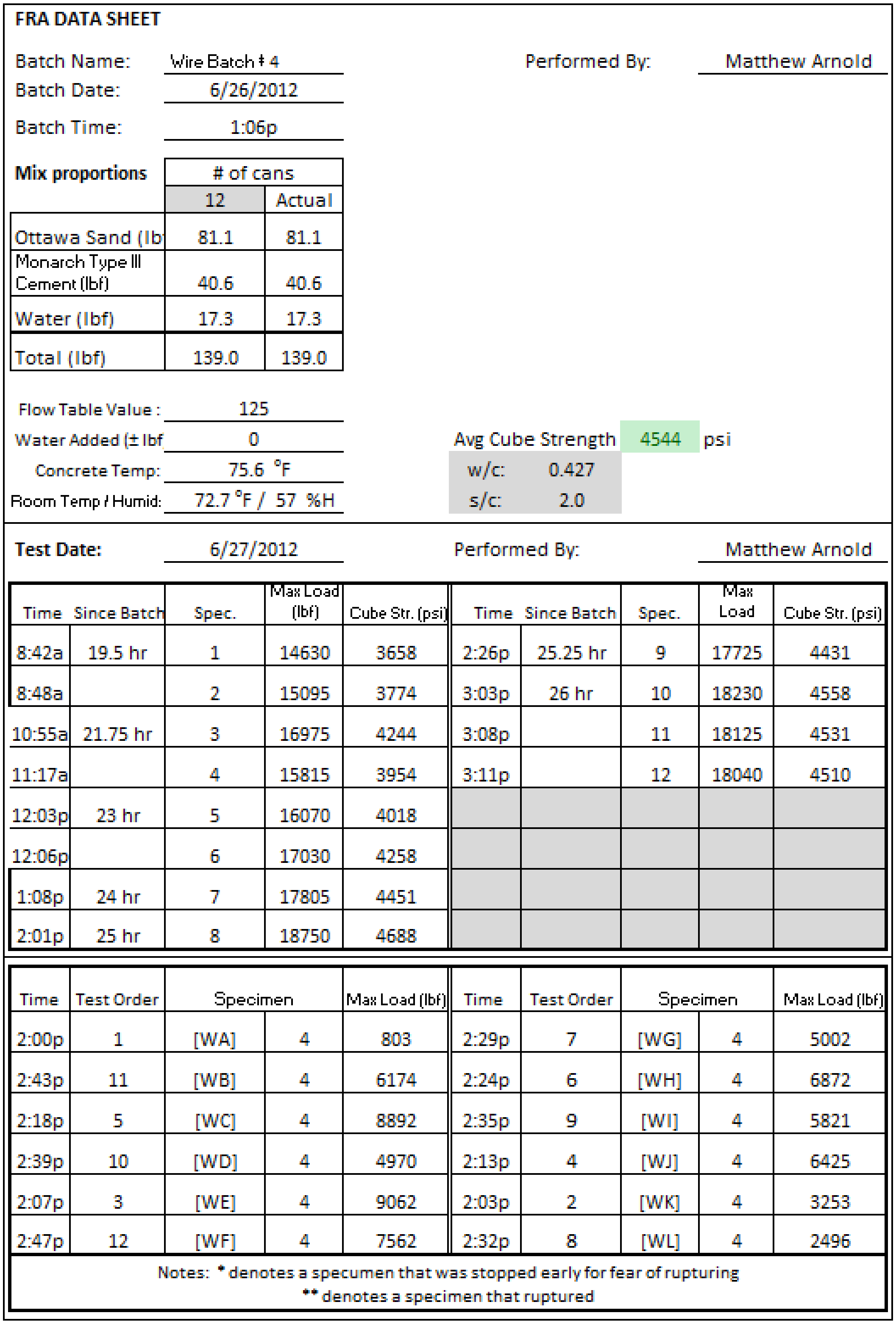
Test Date: 6/22/2012
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:33a	18.25 hr	1	17430	4358	10:59a		9	18145	4536
8:35a	DEFECT	2	15810	3953					
8:37a		3	16910	4228					
9:12a	19 hr	4	17025	4256					
9:50a	19.5 hr	5	18125	4531					
10:11a	20 hr	6	18485	4621					
10:34a	20.25 hr	7	17825	4456					
10:57a	20.75 hr	8	18230	4558					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:55a	1	[WA]	3	644	9:58a	2	[WG]	3	5229
10:12a	5	[WB]	3	6672	10:17a	6	[WH]	3	7140
10:02a	3	[WC]	3	8363	10:07a	4	[WI]	3	6750
10:41a	11	[WD]	3	5484	10:28a	8	[WJ]	3	7688
10:22a	7	[WE]	3	9218 *	10:45a	12	[WK]	3	4174
10:33a	9	[WF]	3	8552	10:38a	10	[WL]	3	2660

Notes: * denotes a specumen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure D.3 As-received wires, batch summary #3 (Ottawa sand)



FRA DATA SHEET

Batch Name: Wire Batch # 4

Performed By: Matthew Arnold

Batch Date: 6/26/2012

Batch Time: 1:06p

Mix proportions	# of cans	
	12	Actual
Ottawa Sand (lb	81.1	81.1
Monarch Type III Cement (lbf)	40.6	40.6
Water (lbf)	17.3	17.3
Total (lbf)	139.0	139.0

Flow Table Value : 125

Water Added (± lbf 0

Concrete Temp: 75.6 °F

Room Temp / Humid: 72.7 °F / 57 %H

Avg Cube Strength 4544 psi

w/c: 0.427

s/c: 2.0

Test Date: 6/27/2012

Performed By: Matthew Arnold

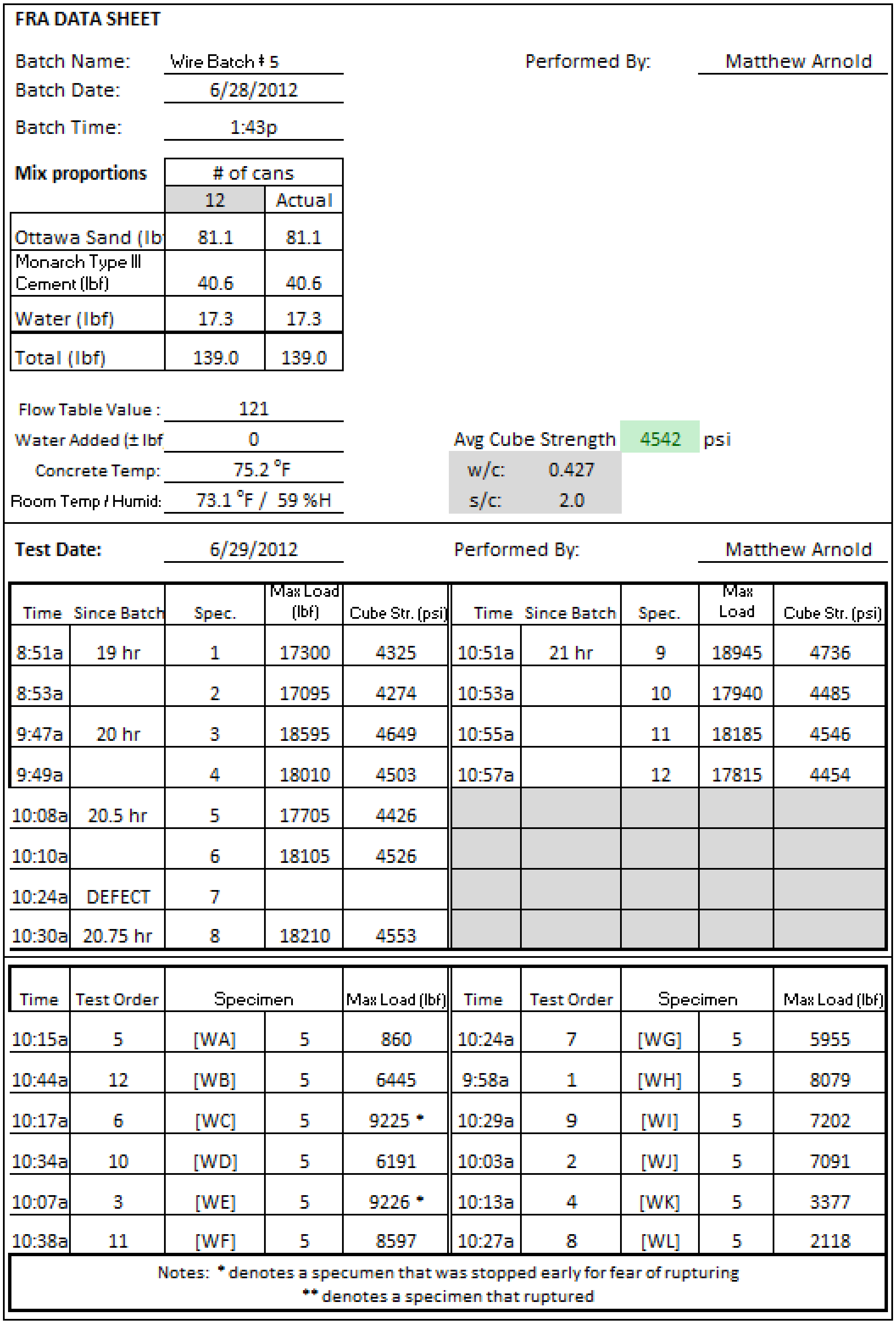
Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:42a	19.5 hr	1	14630	3658	2:26p	25.25 hr	9	17725	4431
8:48a		2	15095	3774	3:03p	26 hr	10	18230	4558
10:55a	21.75 hr	3	16975	4244	3:08p		11	18125	4531
11:17a		4	15815	3954	3:11p		12	18040	4510
12:03p	23 hr	5	16070	4018					
12:06p		6	17030	4258					
1:08p	24 hr	7	17805	4451					
2:01p	25 hr	8	18750	4688					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
2:00p	1	[WA]	4	803	2:29p	7	[WG]	4	5002
2:43p	11	[WB]	4	6174	2:24p	6	[WH]	4	6872
2:18p	5	[WC]	4	8892	2:35p	9	[WI]	4	5821
2:39p	10	[WD]	4	4970	2:13p	4	[WJ]	4	6425
2:07p	3	[WE]	4	9062	2:03p	2	[WK]	4	3253
2:47p	12	[WF]	4	7562	2:32p	8	[WL]	4	2496

Notes: * denotes a specumen that was stopped early for fear of rupturing

** denotes a specimen that ruptured

Figure D.4 As-received wires, batch summary #4 (Ottawa sand)



FRA DATA SHEET

Batch Name: Wire Batch # 5

Performed By: Matthew Arnold

Batch Date: 6/28/2012

Batch Time: 1:43p

Mix proportions	# of cans	
	12	Actual
Ottawa Sand (lb	81.1	81.1
Monarch Type III Cement (lbf)	40.6	40.6
Water (lbf)	17.3	17.3
Total (lbf)	139.0	139.0

Flow Table Value : 121

Water Added (± lbf 0

Concrete Temp: 75.2 °F

Room Temp / Humid: 73.1 °F / 59 %H

Avg Cube Strength 4542 psi

w/c: 0.427

s/c: 2.0

Test Date: 6/29/2012

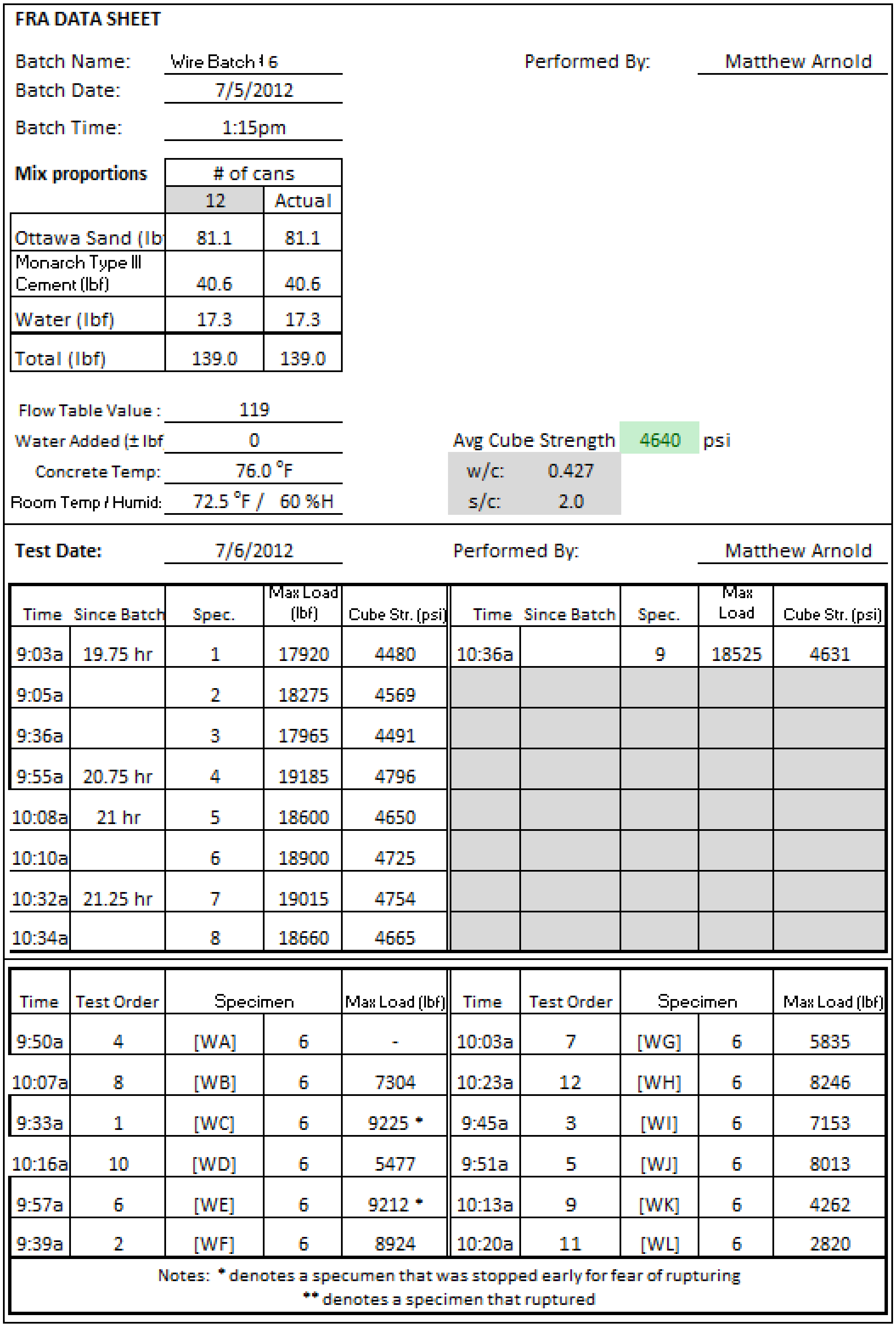
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:51a	19 hr	1	17300	4325	10:51a	21 hr	9	18945	4736
8:53a		2	17095	4274	10:53a		10	17940	4485
9:47a	20 hr	3	18595	4649	10:55a		11	18185	4546
9:49a		4	18010	4503	10:57a		12	17815	4454
10:08a	20.5 hr	5	17705	4426					
10:10a		6	18105	4526					
10:24a	DEFECT	7							
10:30a	20.75 hr	8	18210	4553					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
10:15a	5	[WA]	5	860	10:24a	7	[WG]	5	5955
10:44a	12	[WB]	5	6445	9:58a	1	[WH]	5	8079
10:17a	6	[WC]	5	9225 *	10:29a	9	[WI]	5	7202
10:34a	10	[WD]	5	6191	10:03a	2	[WJ]	5	7091
10:07a	3	[WE]	5	9226 *	10:13a	4	[WK]	5	3377
10:38a	11	[WF]	5	8597	10:27a	8	[WL]	5	2118

Notes: * denotes a specumen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure D.5 As-received wires, batch summary #5 (Ottawa sand)



FRA DATA SHEET

Batch Name: Wire Batch # 6

Performed By: Matthew Arnold

Batch Date: 7/5/2012

Batch Time: 1:15pm

Mix proportions	# of cans	
	12	Actual
Ottawa Sand (lb	81.1	81.1
Monarch Type III Cement (lbf)	40.6	40.6
Water (lbf)	17.3	17.3
Total (lbf)	139.0	139.0

Flow Table Value : 119

Water Added (± lbf 0

Concrete Temp: 76.0 °F

Room Temp / Humid: 72.5 °F / 60 %H

Avg Cube Strength 4640 psi

w/c: 0.427

s/c: 2.0

Test Date: 7/6/2012

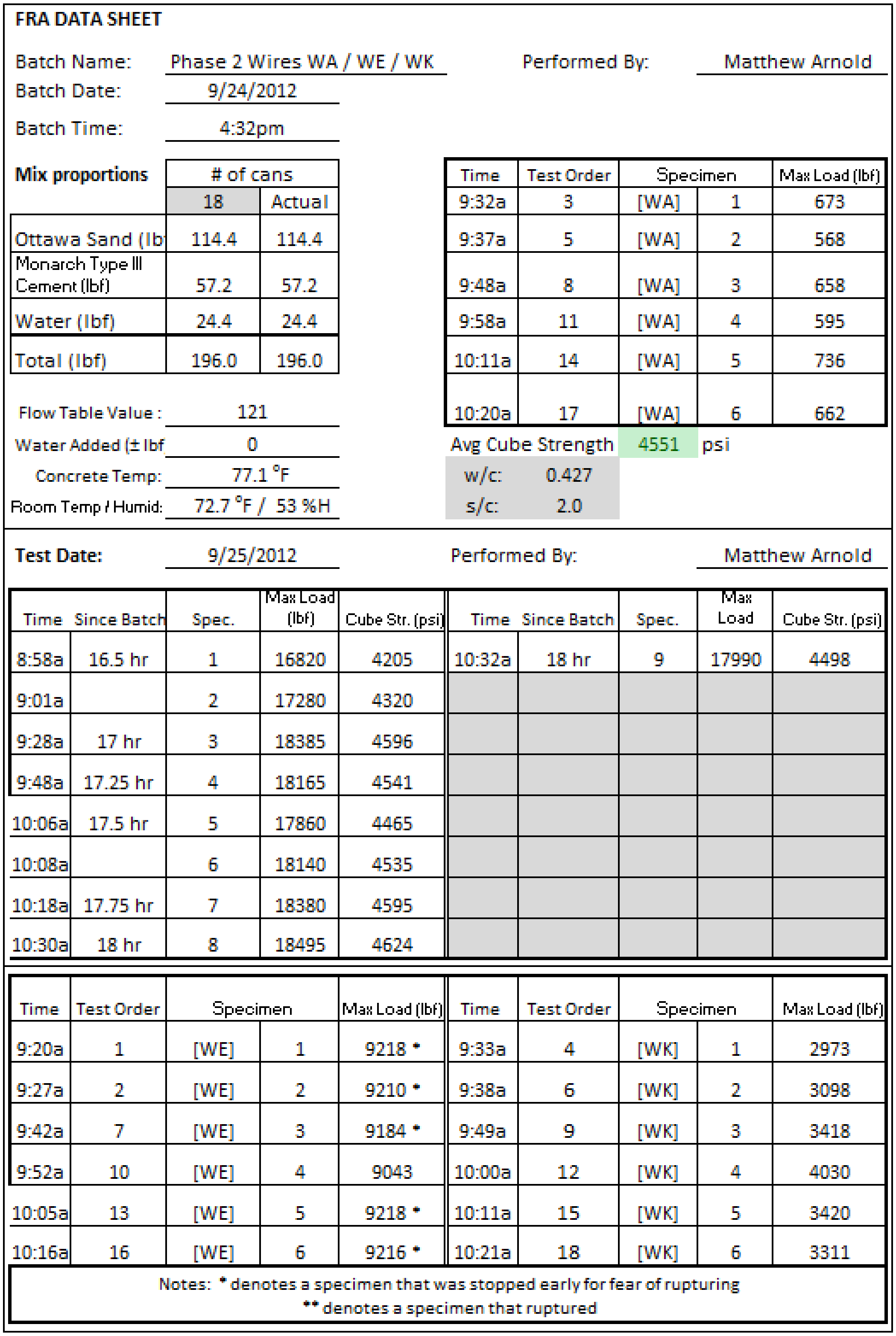
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
9:03a	19.75 hr	1	17920	4480	10:36a		9	18525	4631
9:05a		2	18275	4569					
9:36a		3	17965	4491					
9:55a	20.75 hr	4	19185	4796					
10:08a	21 hr	5	18600	4650					
10:10a		6	18900	4725					
10:32a	21.25 hr	7	19015	4754					
10:34a		8	18660	4665					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:50a	4	[WA]	6	-	10:03a	7	[WG]	6	5835
10:07a	8	[WB]	6	7304	10:23a	12	[WH]	6	8246
9:33a	1	[WC]	6	9225 *	9:45a	3	[WI]	6	7153
10:16a	10	[WD]	6	5477	9:51a	5	[WJ]	6	8013
9:57a	6	[WE]	6	9212 *	10:13a	9	[WK]	6	4262
9:39a	2	[WF]	6	8924	10:20a	11	[WL]	6	2820

Notes: * denotes a specumen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure D.6 As-received wires, batch summary #6 (Ottawa sand)



FRA DATA SHEET

Batch Name: Phase 2 Wires WA / WE / WK

Performed By: Matthew Arnold

Batch Date: 9/24/2012

Batch Time: 4:32pm

Mix proportions	# of cans	
	18	Actual
Ottawa Sand (lb	114.4	114.4
Monarch Type III Cement (lbf)	57.2	57.2
Water (lbf)	24.4	24.4
Total (lbf)	196.0	196.0

Time	Test Order	Specimen		Max Load (lbf)
9:32a	3	[WA]	1	673
9:37a	5	[WA]	2	568
9:48a	8	[WA]	3	658
9:58a	11	[WA]	4	595
10:11a	14	[WA]	5	736
10:20a	17	[WA]	6	662

Flow Table Value : 121

Water Added (± lbf 0

Concrete Temp: 77.1 °F

Room Temp / Humid: 72.7 °F / 53 %H

Avg Cube Strength 4551 psi

w/c: 0.427

s/c: 2.0

Test Date: 9/25/2012

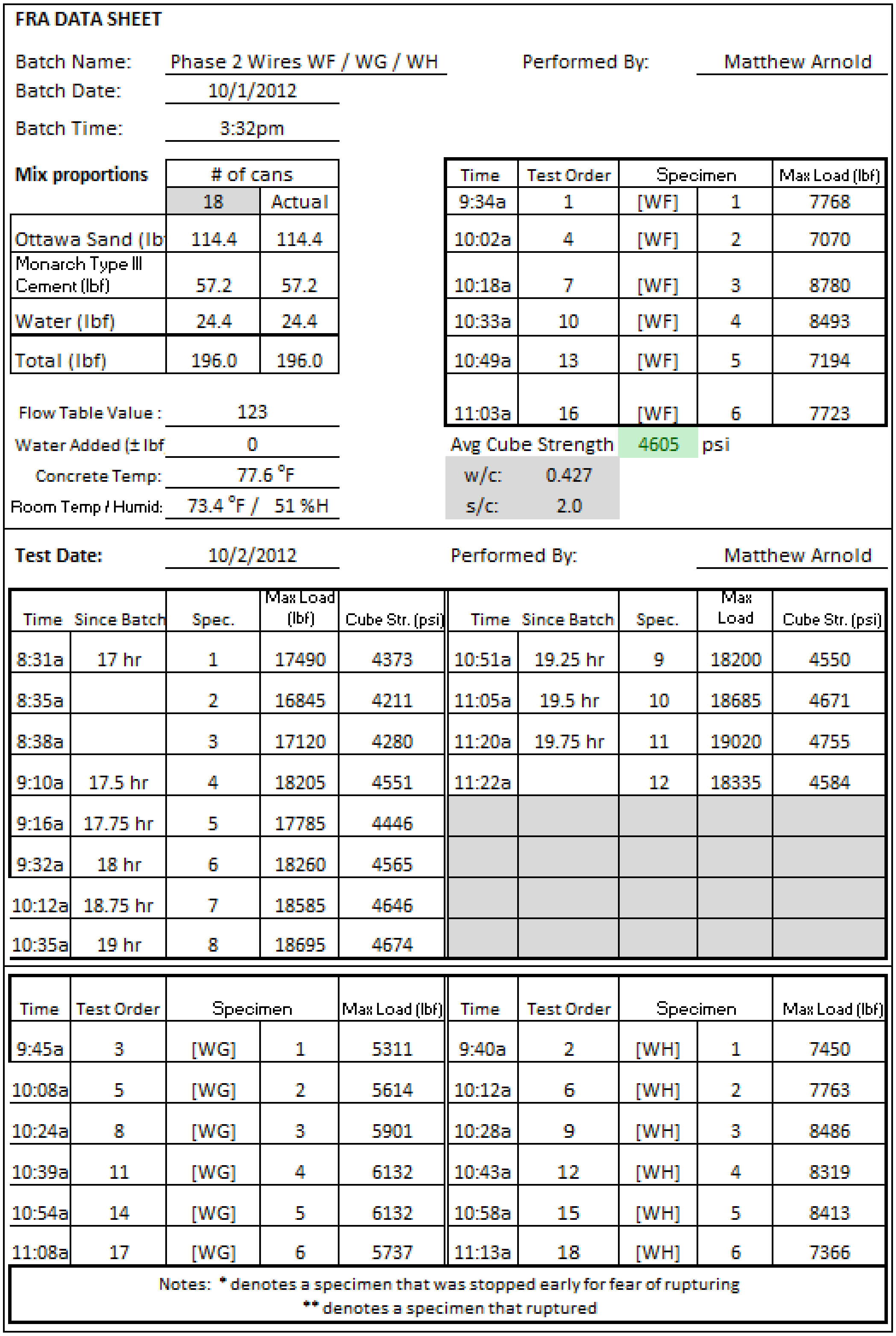
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:58a	16.5 hr	1	16820	4205	10:32a	18 hr	9	17990	4498
9:01a		2	17280	4320					
9:28a	17 hr	3	18385	4596					
9:48a	17.25 hr	4	18165	4541					
10:06a	17.5 hr	5	17860	4465					
10:08a		6	18140	4535					
10:18a	17.75 hr	7	18380	4595					
10:30a	18 hr	8	18495	4624					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:20a	1	[WE]	1	9218 *	9:33a	4	[WK]	1	2973
9:27a	2	[WE]	2	9210 *	9:38a	6	[WK]	2	3098
9:42a	7	[WE]	3	9184 *	9:49a	9	[WK]	3	3418
9:52a	10	[WE]	4	9043	10:00a	12	[WK]	4	4030
10:05a	13	[WE]	5	9218 *	10:11a	15	[WK]	5	3420
10:16a	16	[WE]	6	9216 *	10:21a	18	[WK]	6	3311

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure D.7 Cleaned wires, batch summary #1 (Ottawa sand)



FRA DATA SHEET

Batch Name: Phase 2 Wires WF / WG / WH

Performed By: Matthew Arnold

Batch Date: 10/1/2012

Batch Time: 3:32pm

Mix proportions	# of cans	
	18	Actual
Ottawa Sand (lb	114.4	114.4
Monarch Type III Cement (lbf)	57.2	57.2
Water (lbf)	24.4	24.4
Total (lbf)	196.0	196.0

Time	Test Order	Specimen		Max Load (lbf)
9:34a	1	[WF]	1	7768
10:02a	4	[WF]	2	7070
10:18a	7	[WF]	3	8780
10:33a	10	[WF]	4	8493
10:49a	13	[WF]	5	7194
11:03a	16	[WF]	6	7723

Flow Table Value : 123

Water Added (± lbf 0

Concrete Temp: 77.6 °F

Room Temp / Humid: 73.4 °F / 51 %H

Avg Cube Strength 4605 psi

w/c: 0.427

s/c: 2.0

Test Date: 10/2/2012

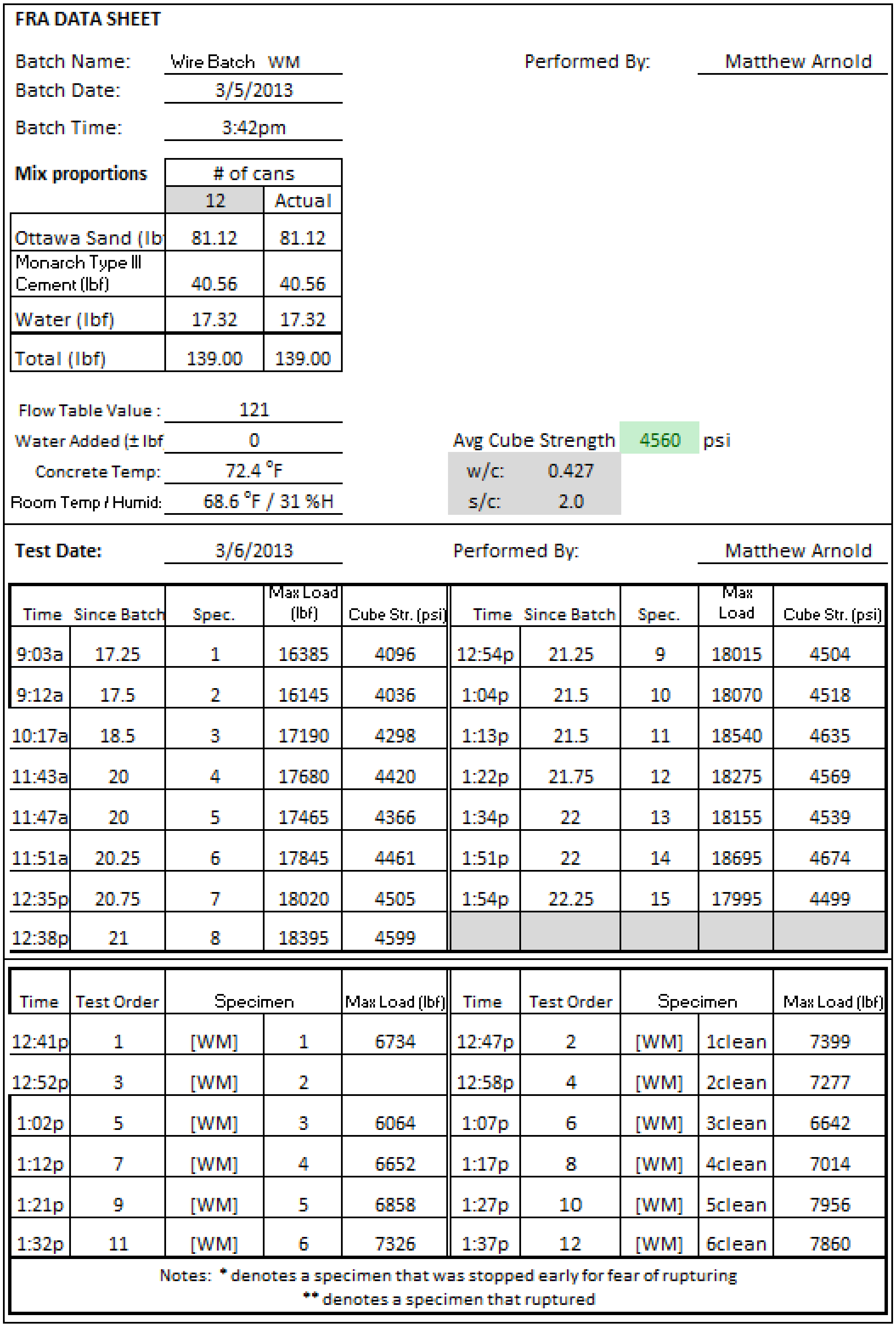
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:31a	17 hr	1	17490	4373	10:51a	19.25 hr	9	18200	4550
8:35a		2	16845	4211	11:05a	19.5 hr	10	18685	4671
8:38a		3	17120	4280	11:20a	19.75 hr	11	19020	4755
9:10a	17.5 hr	4	18205	4551	11:22a		12	18335	4584
9:16a	17.75 hr	5	17785	4446					
9:32a	18 hr	6	18260	4565					
10:12a	18.75 hr	7	18585	4646					
10:35a	19 hr	8	18695	4674					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
9:45a	3	[WG]	1	5311	9:40a	2	[WH]	1	7450
10:08a	5	[WG]	2	5614	10:12a	6	[WH]	2	7763
10:24a	8	[WG]	3	5901	10:28a	9	[WH]	3	8486
10:39a	11	[WG]	4	6132	10:43a	12	[WH]	4	8319
10:54a	14	[WG]	5	6132	10:58a	15	[WH]	5	8413
11:08a	17	[WG]	6	5737	11:13a	18	[WH]	6	7366

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure D.8 Cleaned wires, batch summary #2 (Ottawa sand)



FRA DATA SHEET

Batch Name: Wire Batch WM

Performed By: Matthew Arnold

Batch Date: 3/5/2013

Batch Time: 3:42pm

Mix proportions	# of cans	
	12	Actual
Ottawa Sand (lb	81.12	81.12
Monarch Type III Cement (lbf)	40.56	40.56
Water (lbf)	17.32	17.32
Total (lbf)	139.00	139.00

Flow Table Value : 121

Water Added (± lbf: 0

Concrete Temp: 72.4 °F

Room Temp / Humid: 68.6 °F / 31 %H

Avg Cube Strength	4560	psi
w/c:	0.427	
s/c:	2.0	

Test Date: 3/6/2013

Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
9:03a	17.25	1	16385	4096	12:54p	21.25	9	18015	4504
9:12a	17.5	2	16145	4036	1:04p	21.5	10	18070	4518
10:17a	18.5	3	17190	4298	1:13p	21.5	11	18540	4635
11:43a	20	4	17680	4420	1:22p	21.75	12	18275	4569
11:47a	20	5	17465	4366	1:34p	22	13	18155	4539
11:51a	20.25	6	17845	4461	1:51p	22	14	18695	4674
12:35p	20.75	7	18020	4505	1:54p	22.25	15	17995	4499
12:38p	21	8	18395	4599					

Time	Test Order	Specimen		Max Load (lbf)	Time	Test Order	Specimen		Max Load (lbf)
12:41p	1	[WM]	1	6734	12:47p	2	[WM]	1clean	7399
12:52p	3	[WM]	2		12:58p	4	[WM]	2clean	7277
1:02p	5	[WM]	3	6064	1:07p	6	[WM]	3clean	6642
1:12p	7	[WM]	4	6652	1:17p	8	[WM]	4clean	7014
1:21p	9	[WM]	5	6858	1:27p	10	[WM]	5clean	7956
1:32p	11	[WM]	6	7326	1:37p	12	[WM]	6clean	7860

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure D.9 As-received and cleaned wires, batch summary for wire [WM] (Ottawa sand)

Appendix E - Lab Phase, Wire; As-Received and Cleaned Individual Pullout Graphs

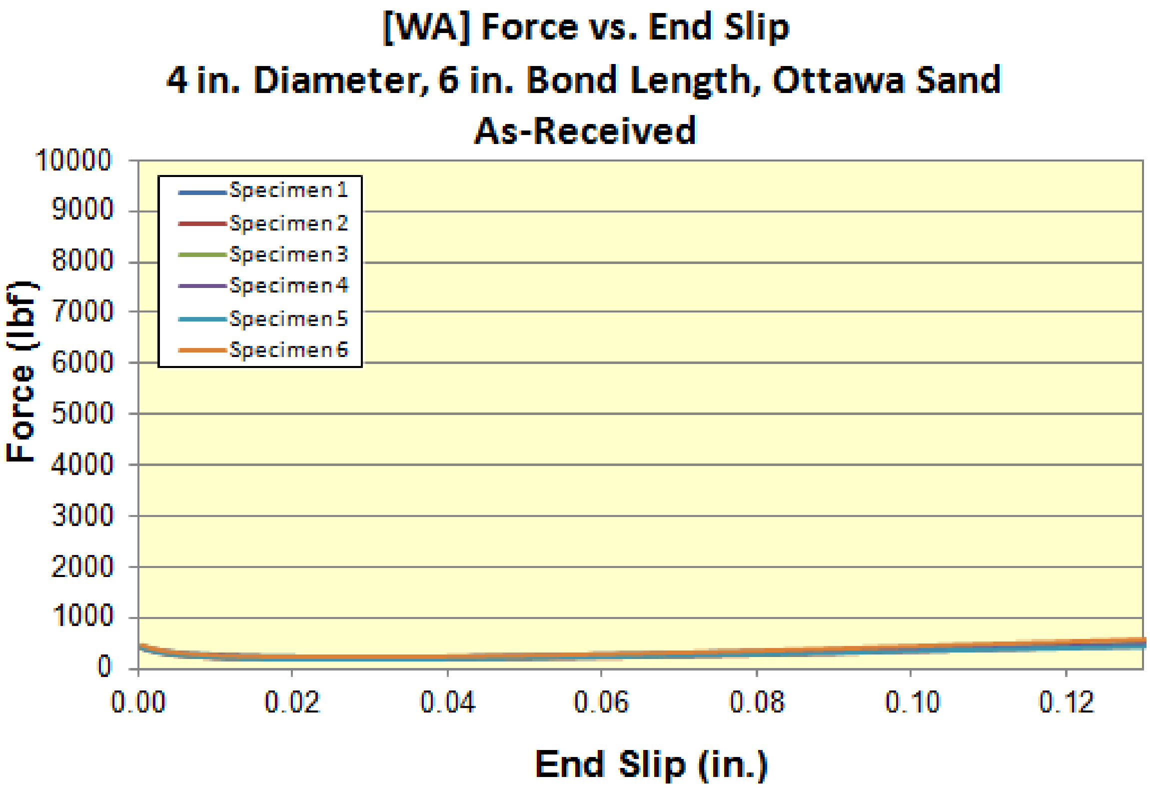


Figure E.1 As-received [WA] force vs. end slip individual graphs

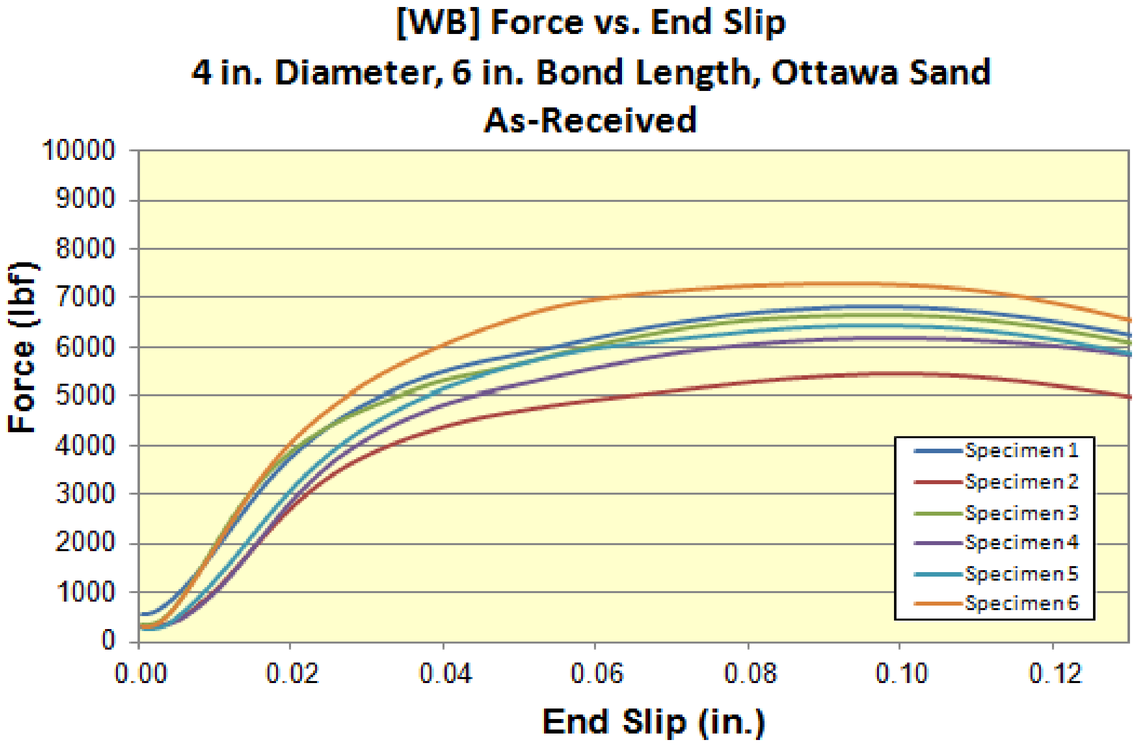


Figure E.2 As-received [WB] force vs. end slip individual graphs

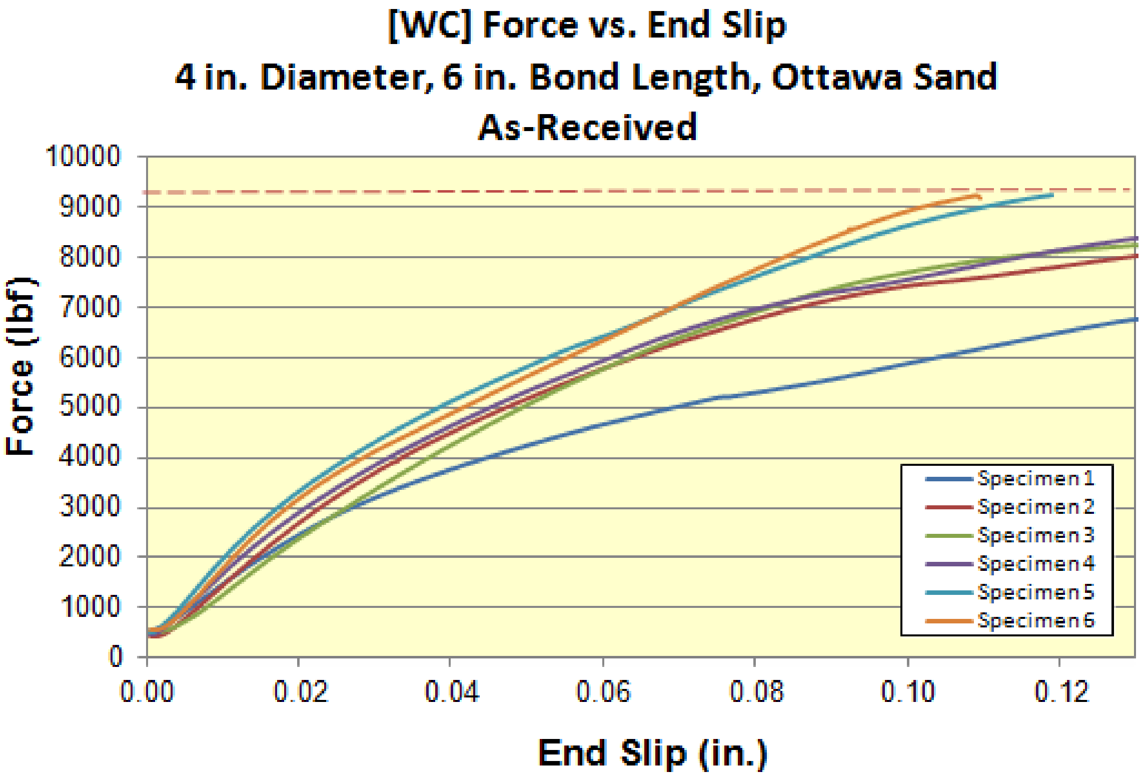


Figure E.3 As-received [WC] force vs. end slip individual graphs

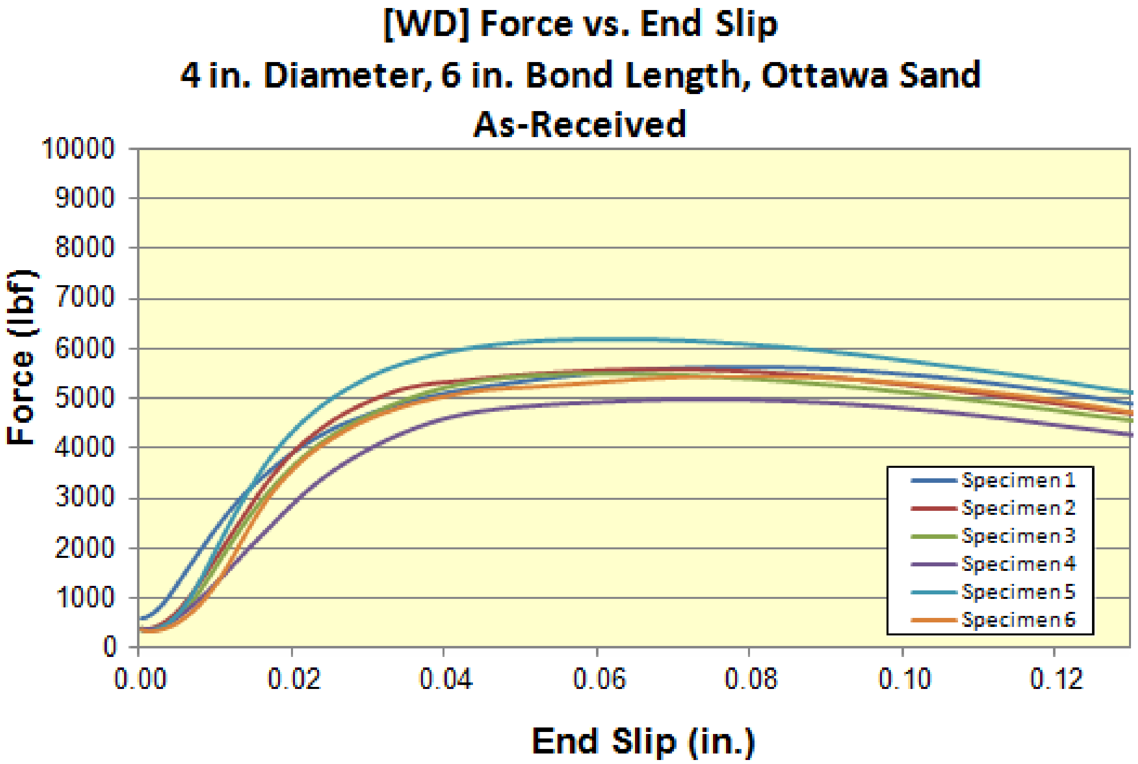


Figure E.4 As-received [WD] force vs. end slip individual graphs

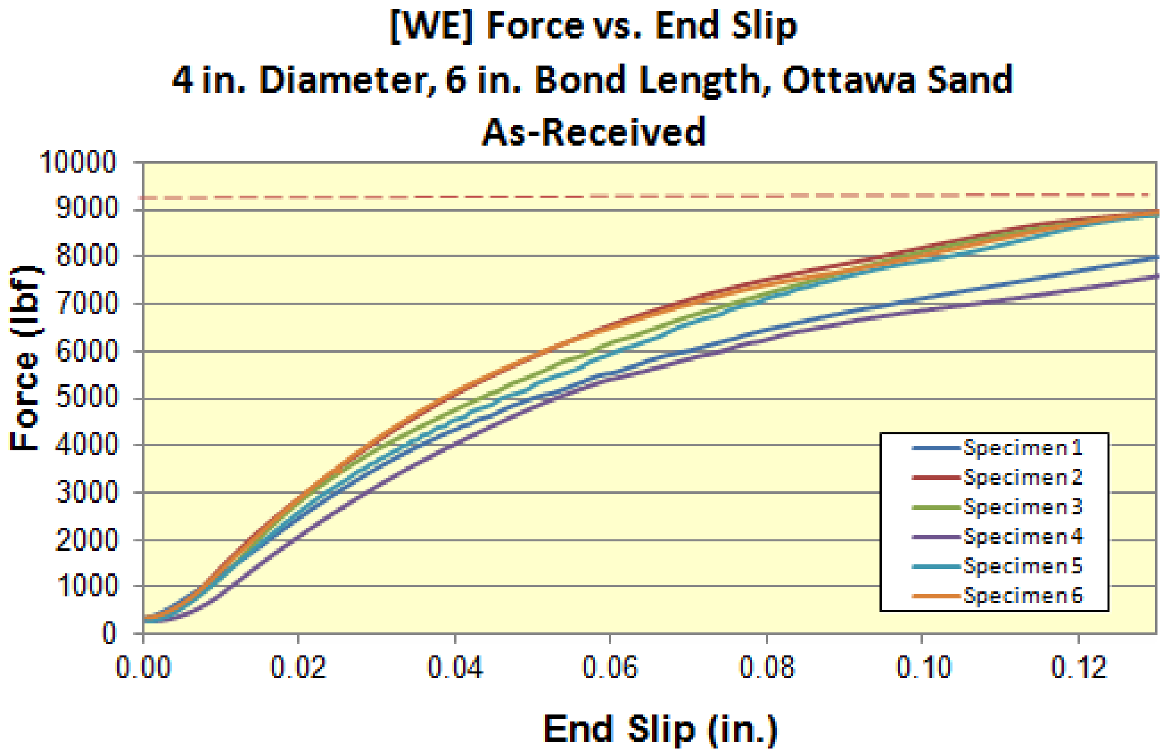


Figure E.5 As-received [WE] force vs. end slip individual graphs

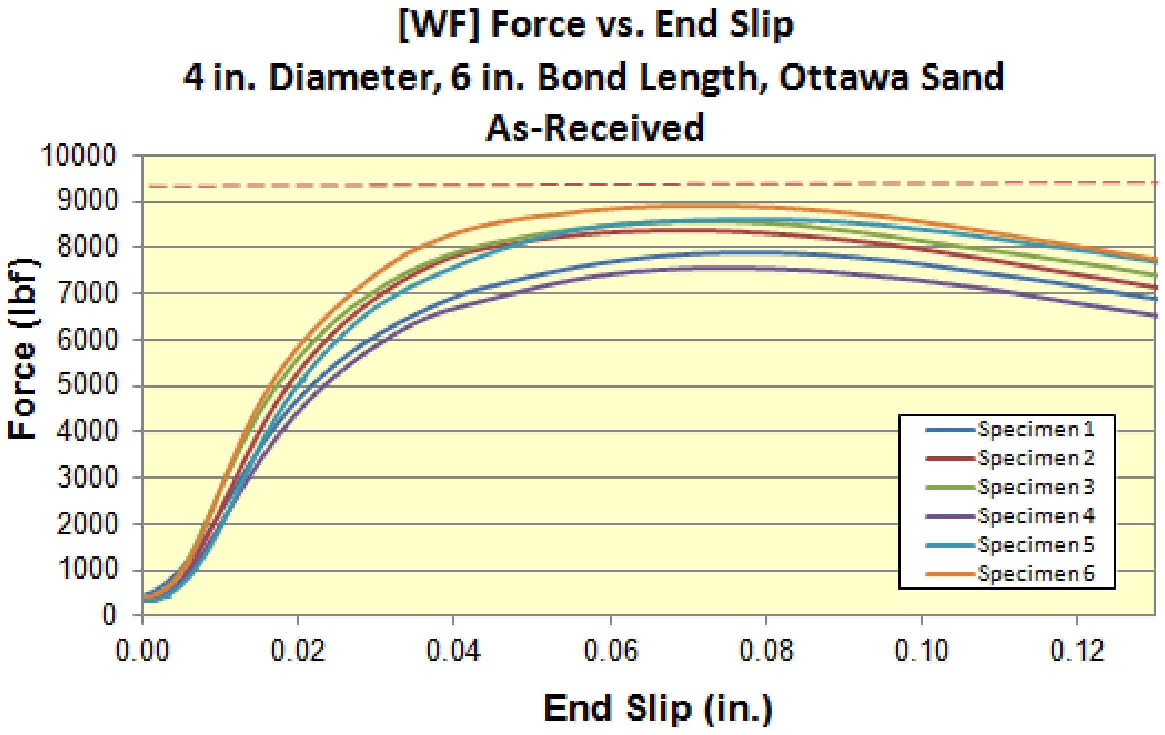


Figure E.6 As-received [WF] force vs. end slip individual graphs

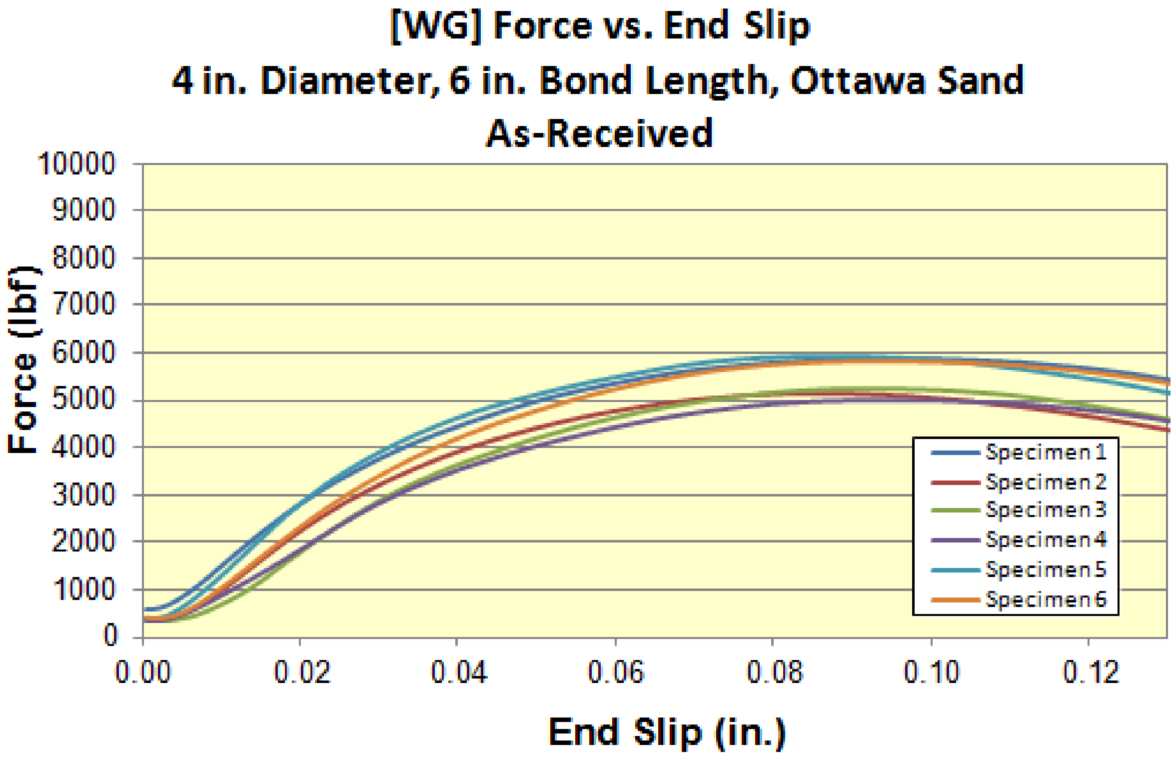


Figure E.7 As-received [WG] force vs. end slip individual graphs

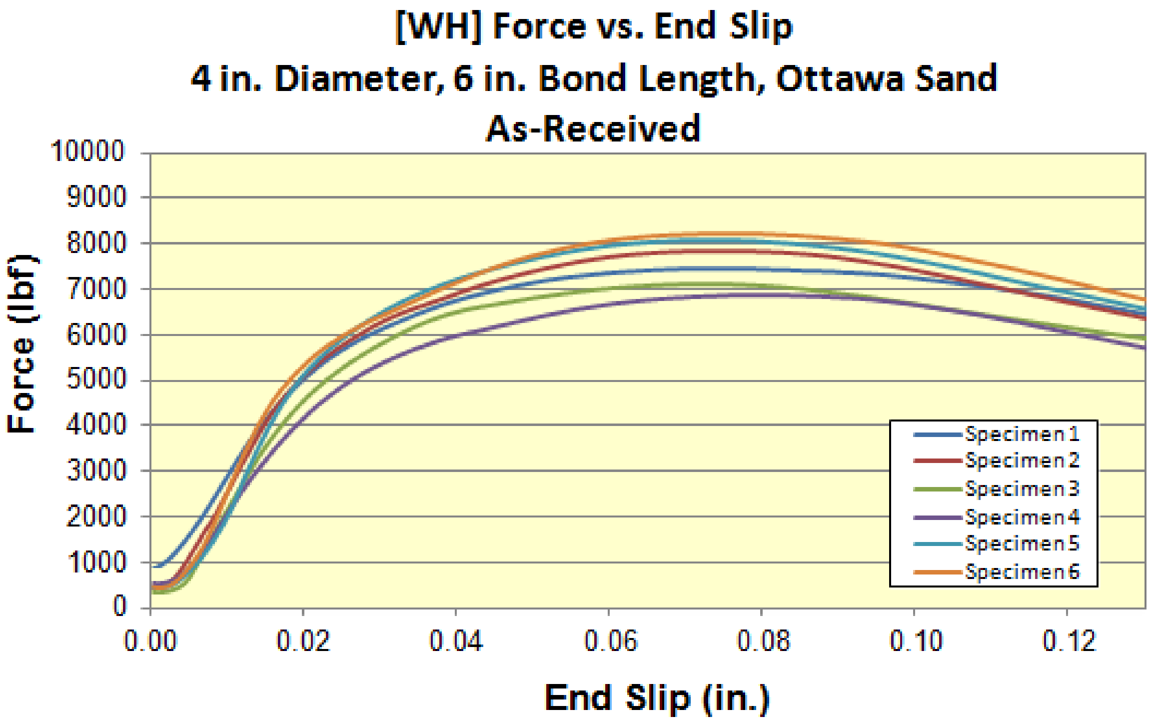


Figure E.8 As-received [WH] force vs. end slip individual graphs

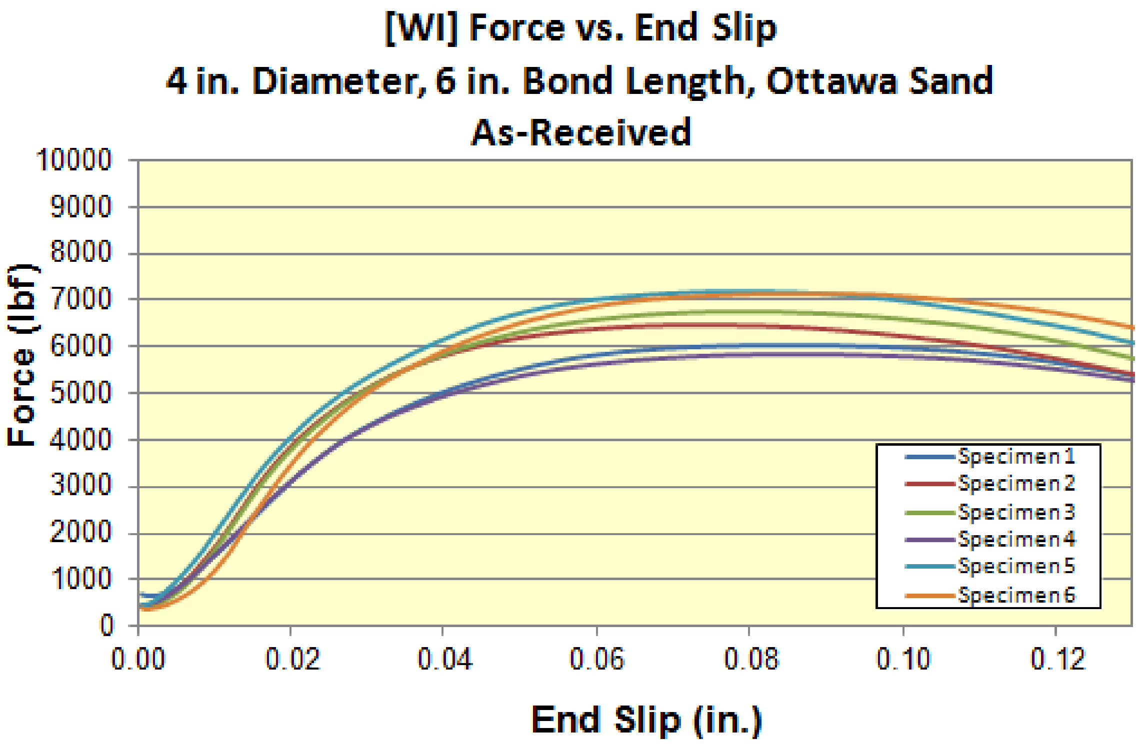


Figure E.9 As-received [WI] force vs. end slip individual graphs

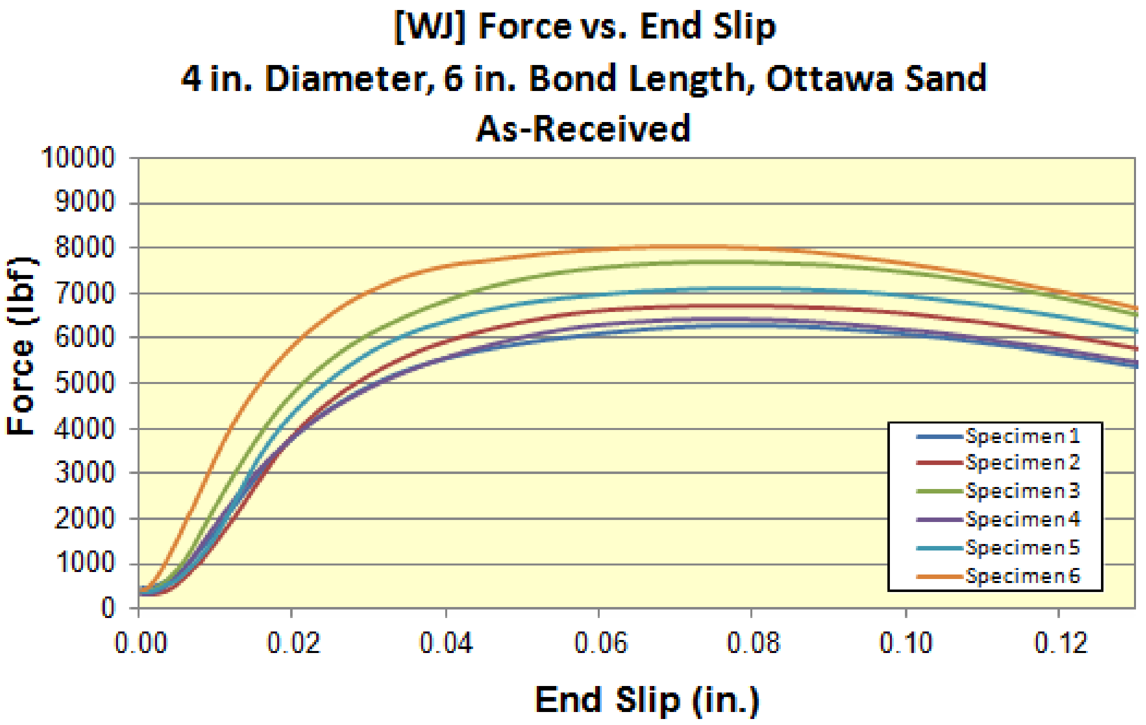


Figure E.10 As-received [WJ] force vs. end slip individual graphs

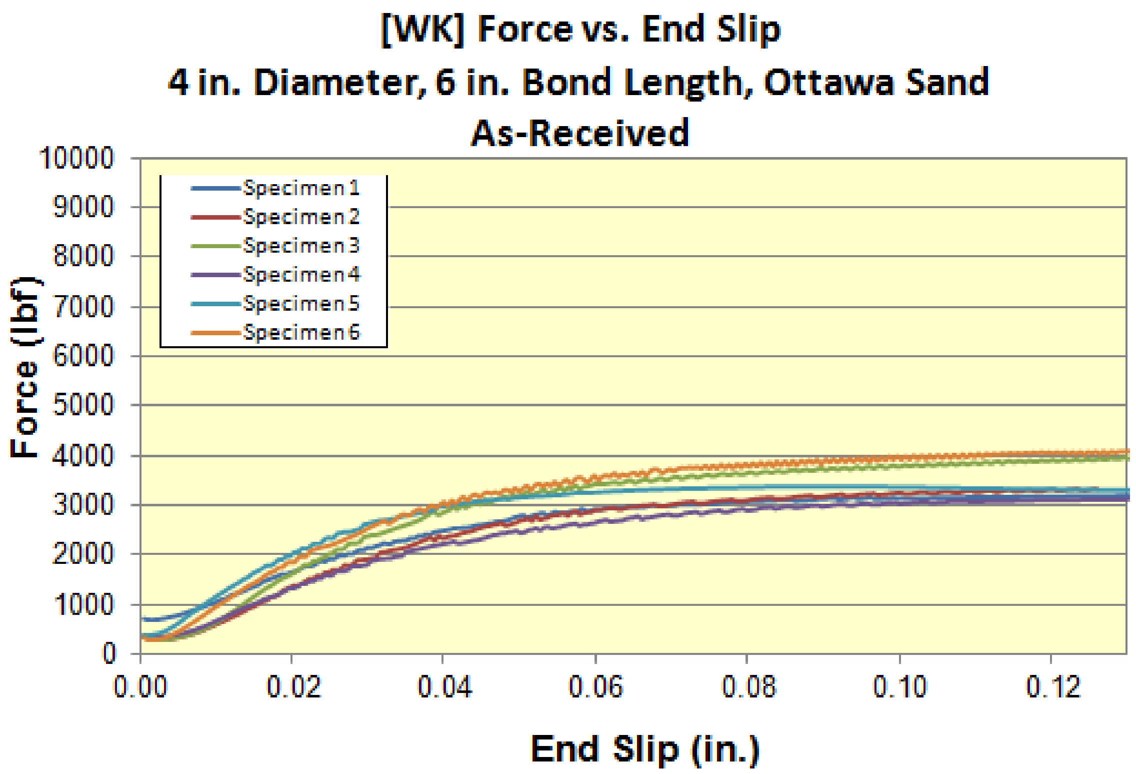


Figure E.11 As-received [WK] force vs. end slip individual graphs

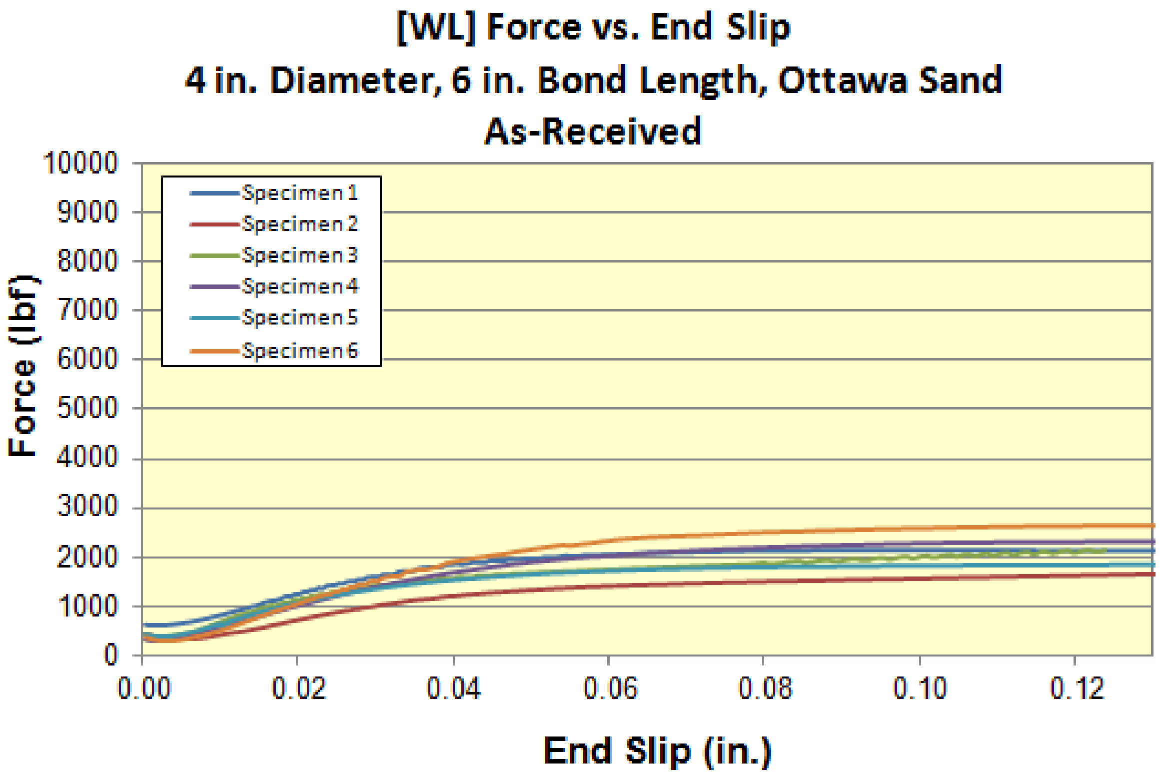


Figure E.12 As-received [WL] force vs. end slip individual graphs

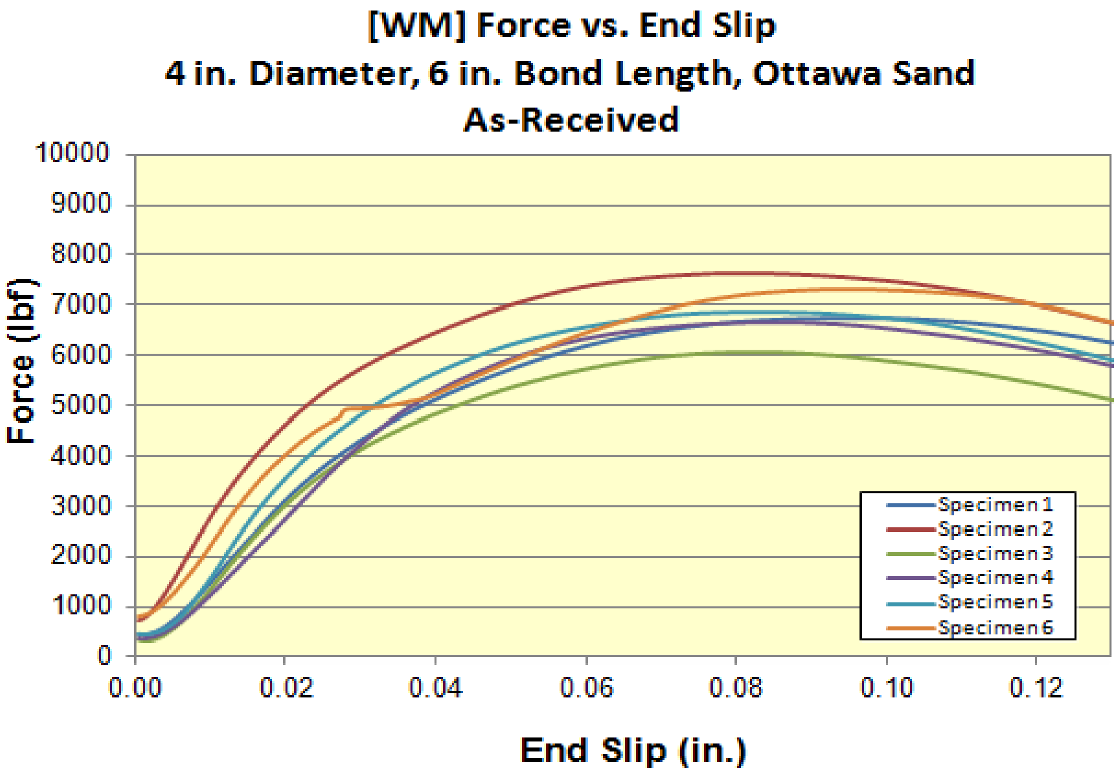


Figure E.13 As-received [WM] force vs. end slip individual graphs

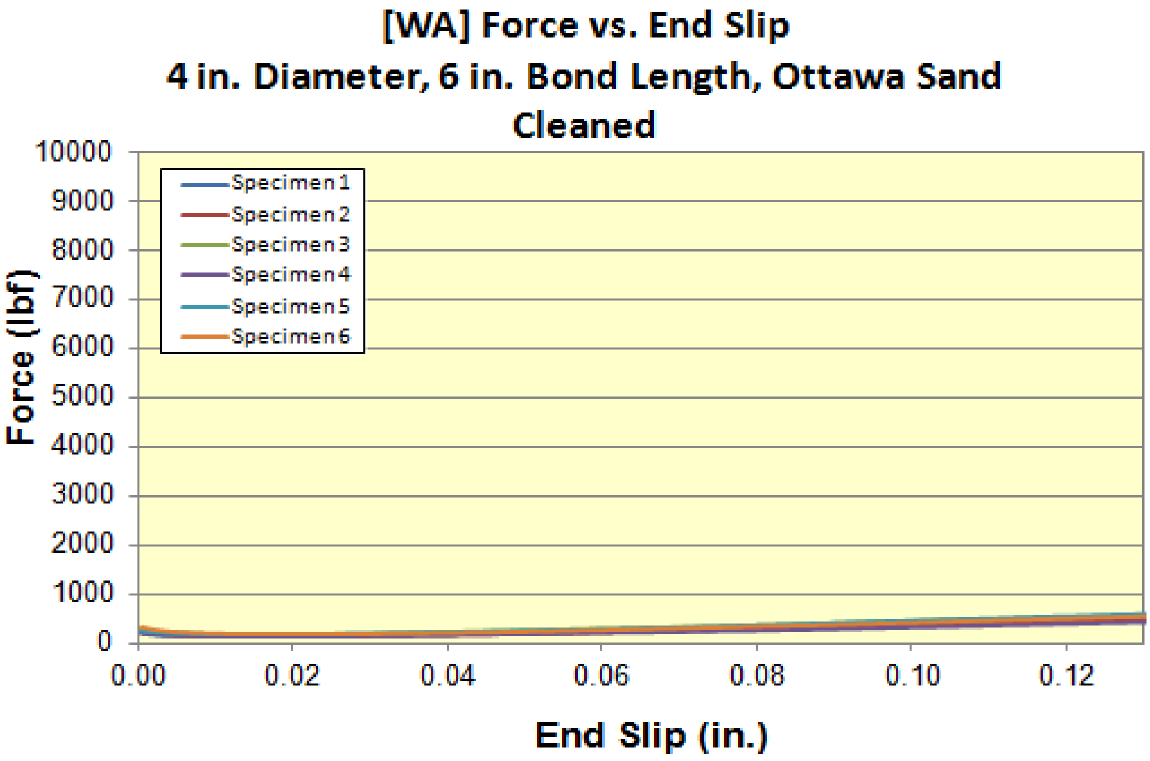


Figure E.14 Cleaned [WA] force vs. end slip individual graphs

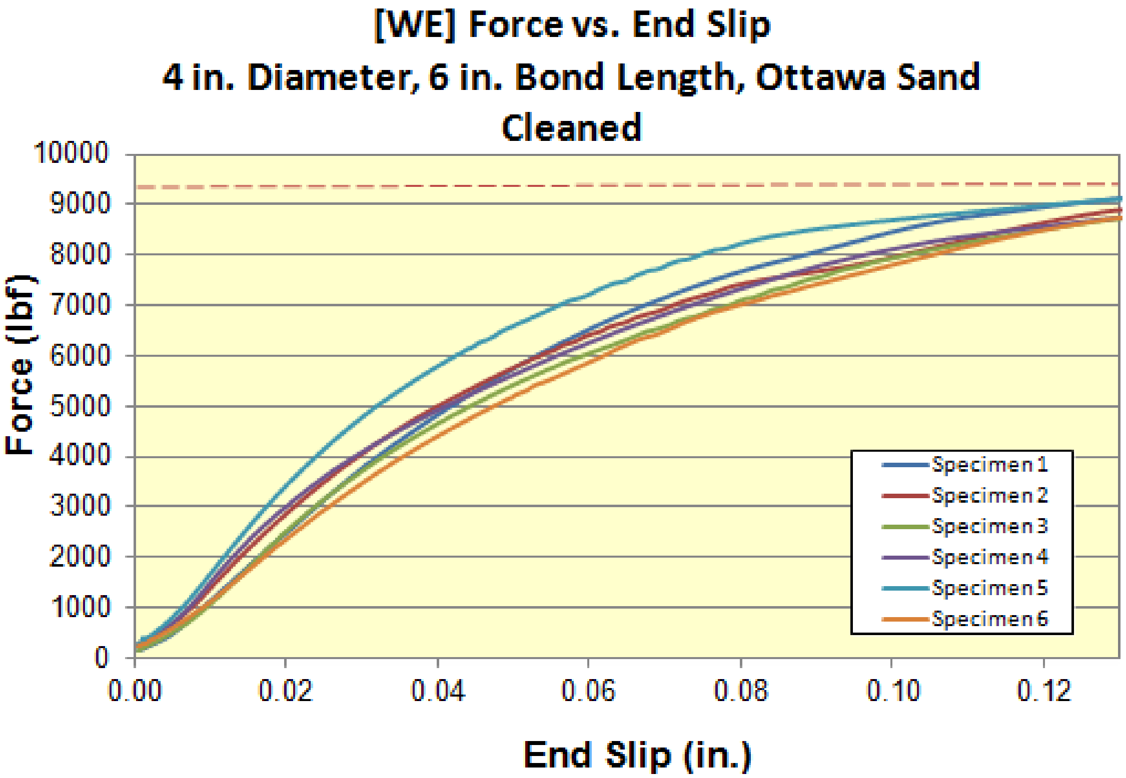


Figure E.15 Cleaned [WE] force vs. end slip individual graphs

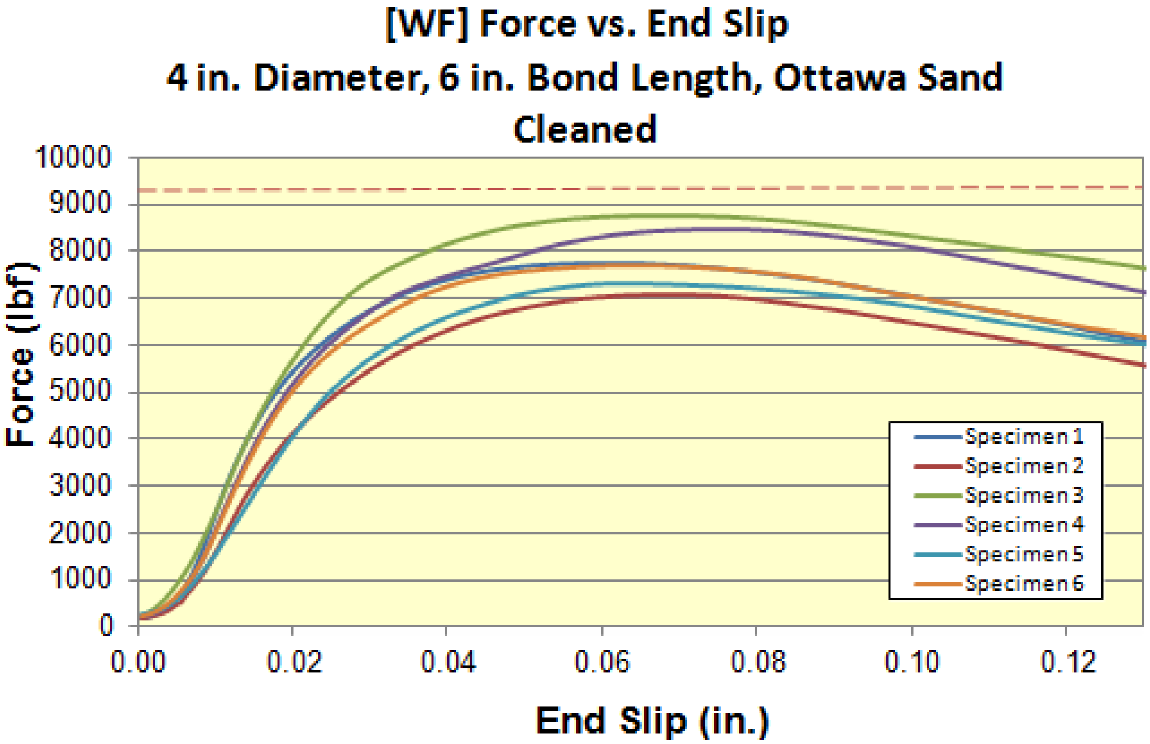


Figure E.16 Cleaned [WF] force vs. end slip individual graphs

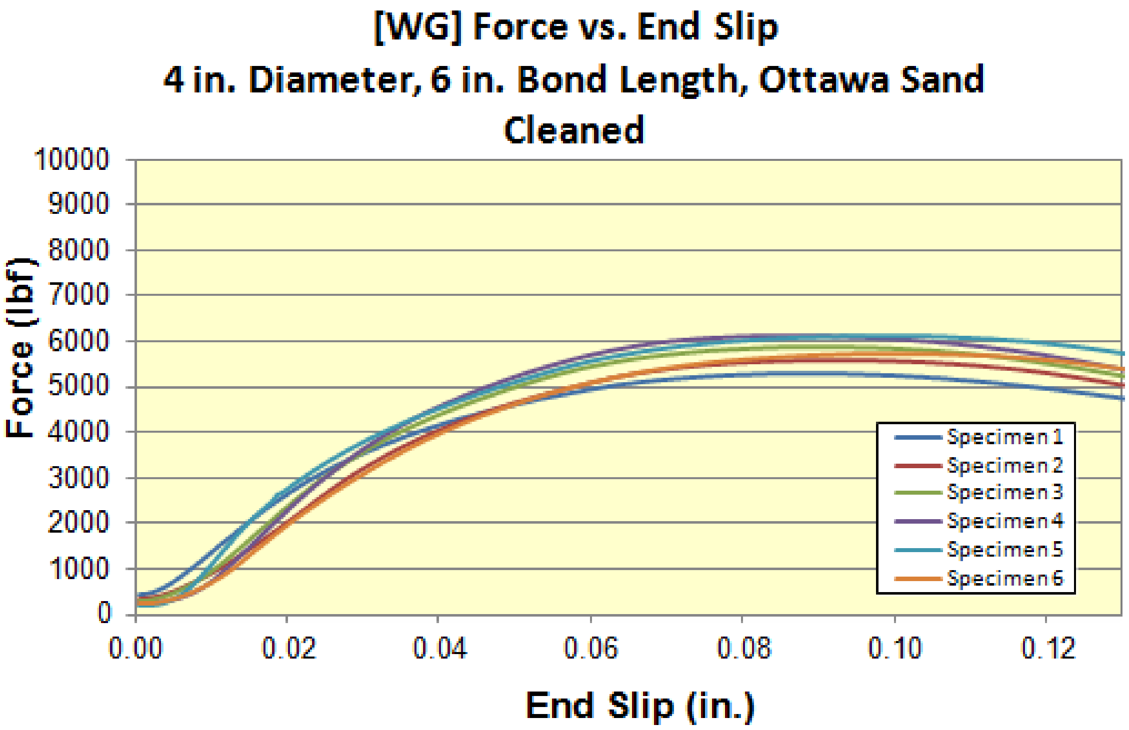


Figure E.17 Cleaned [WG] force vs. end slip individual graphs

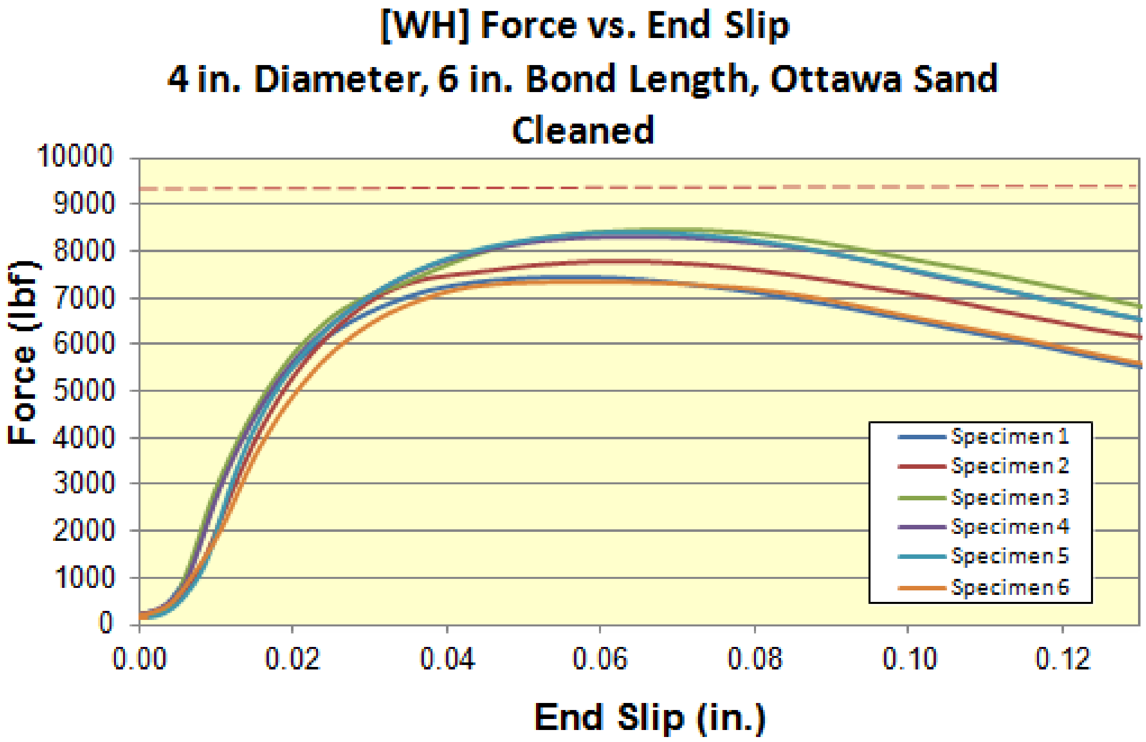


Figure E.18 Cleaned [WH] force vs. end slip individual graphs

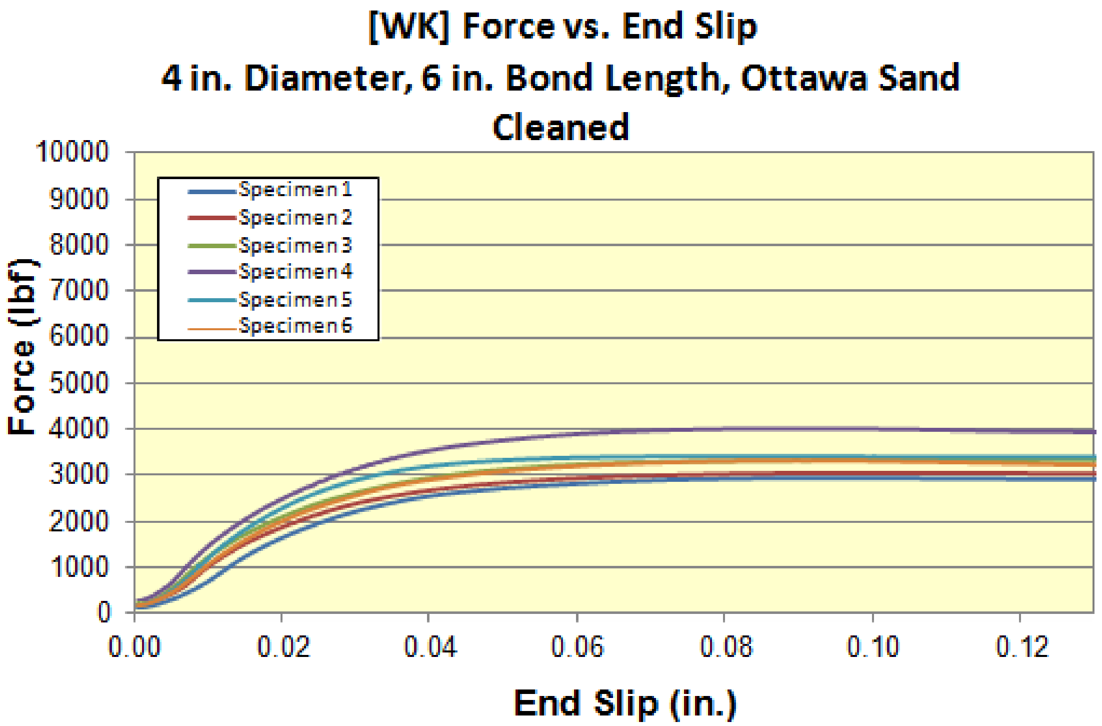


Figure E.19 Cleaned [WK] force vs. end slip individual graphs

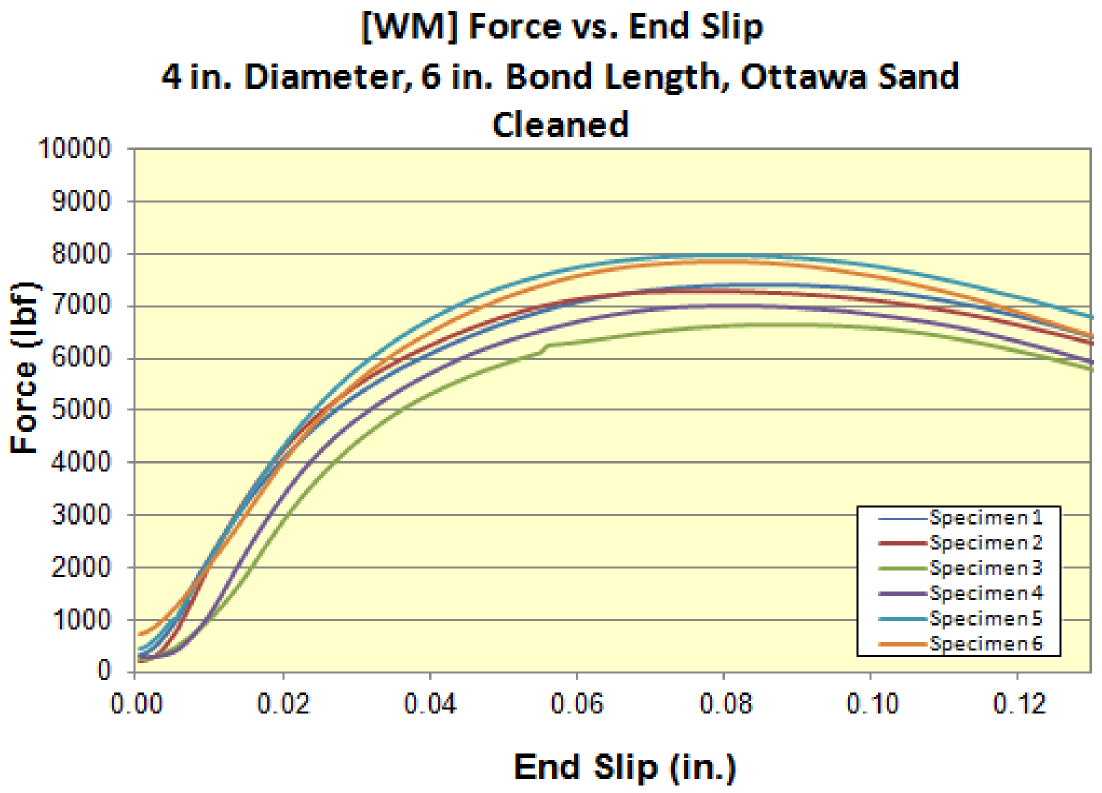
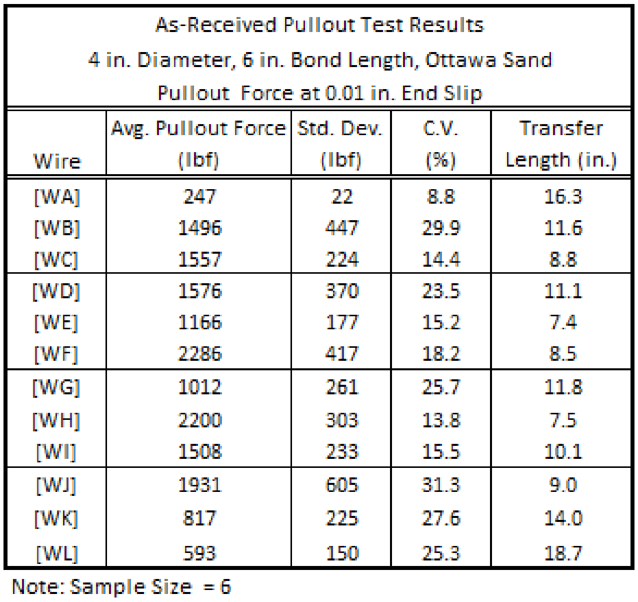


Figure E.20 Cleaned [WM] force vs. end slip individual graphs

Appendix F - Lab Phase, Wire; As-Received Force at Certain End Slip Analysis

Table F.1 As-received wires, pullout force at 0.01 in. end slip



As-Received Pullout Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
Pullout Force at 0.01 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	247	22	8.8	16.3
[WB]	1496	447	29.9	11.6
[WC]	1557	224	14.4	8.8
[WD]	1576	370	23.5	11.1
[WE]	1166	177	15.2	7.4
[WF]	2286	417	18.2	8.5
[WG]	1012	261	25.7	11.8
[WH]	2200	303	13.8	7.5
[WI]	1508	233	15.5	10.1
[WJ]	1931	605	31.3	9.0
[WK]	817	225	27.6	14.0
[WL]	593	150	25.3	18.7

Note: Sample Size = 6

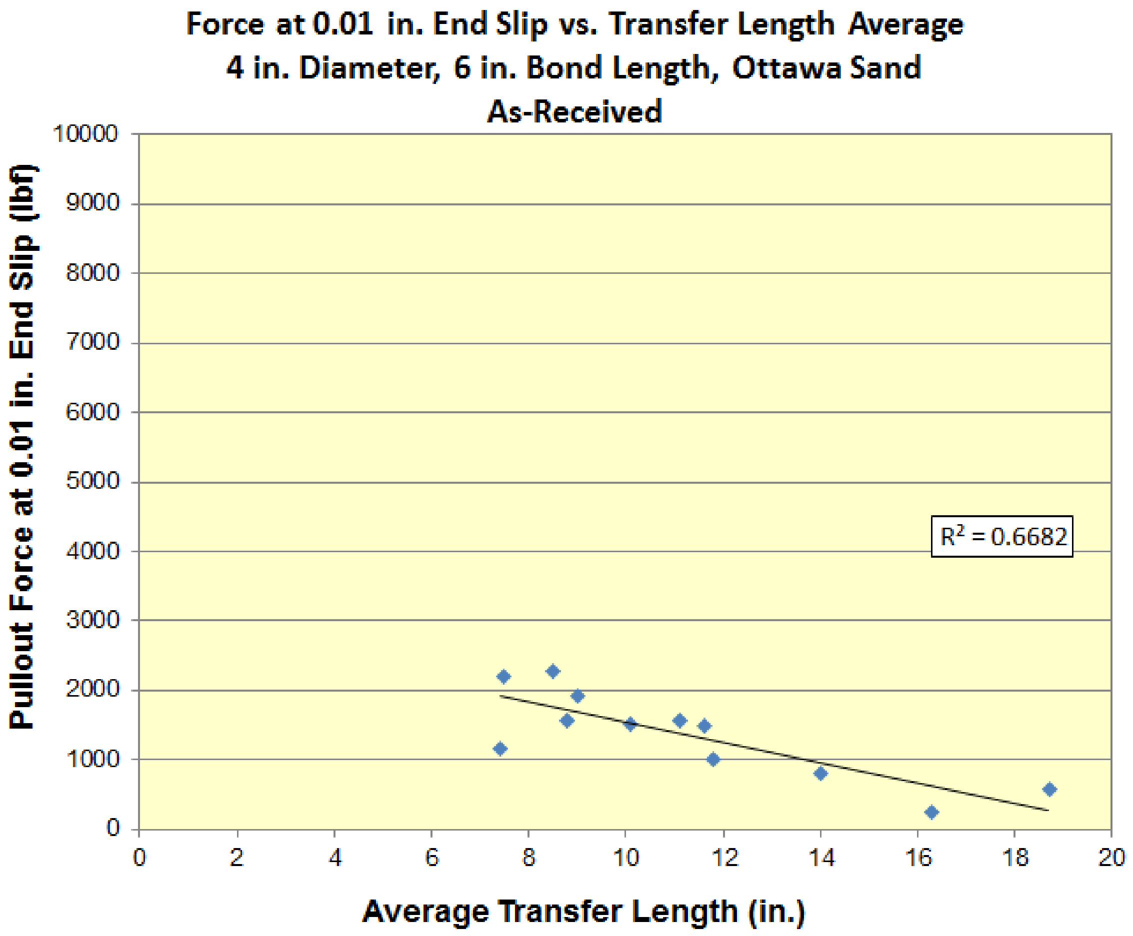


Figure F.1 As-received wires, pullout force at 0.01 in. end slip

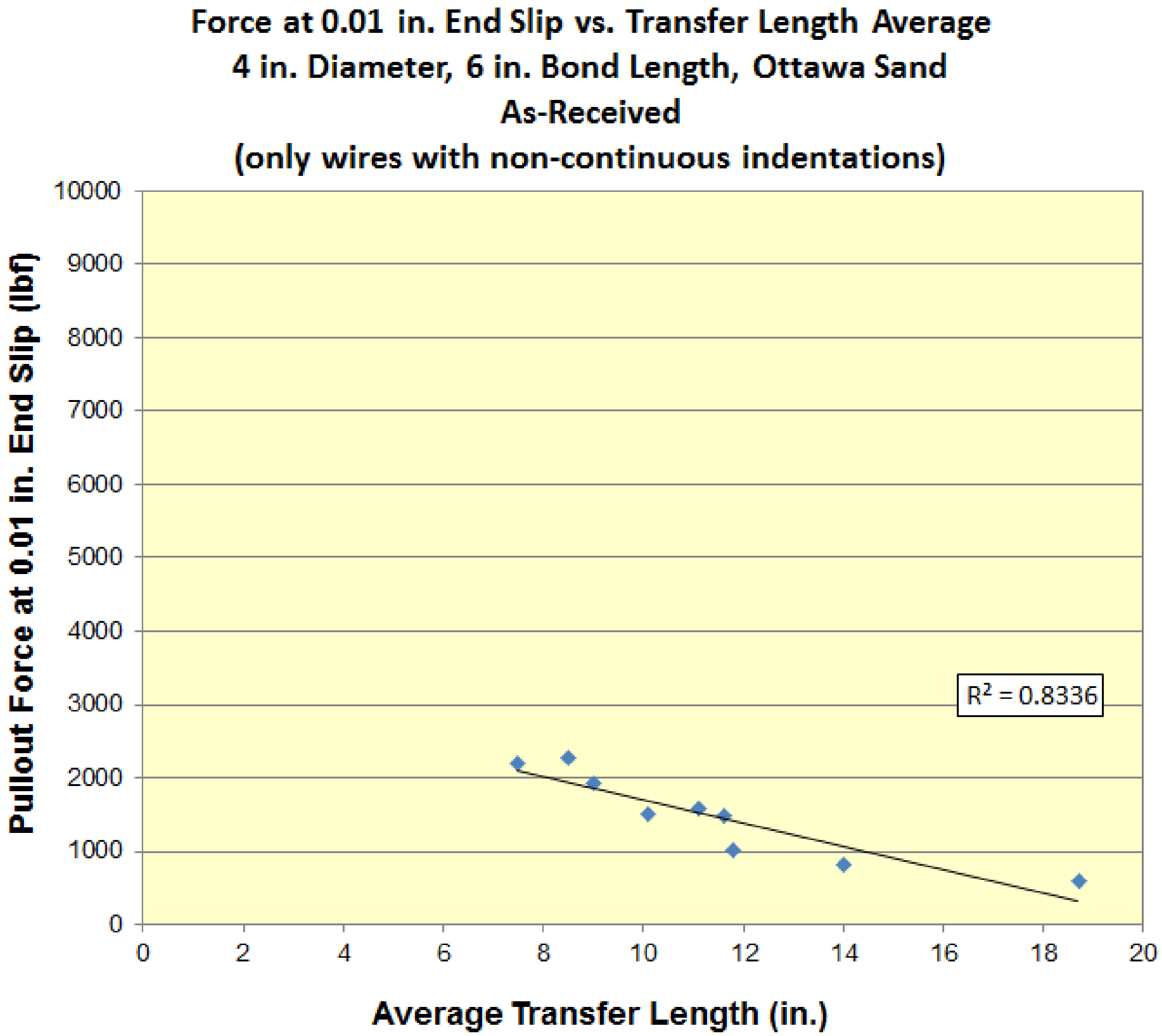


Figure F.2 As-received wires, pullout force at 0.01 in. end slip (individual-indents only)

Table F.2 As-received wires, pullout force at 0.02 in. end slip

As-Received Pullout Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
Pullout Force at 0.02 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	213	19	9.1	16.3
[WB]	3366	530	15.8	11.6
[WC]	2794	340	12.2	8.8
[WD]	3616	445	12.3	11.1
[WE]	2580	288	11.2	7.4
[WF]	5135	511	10.0	8.5
[WG]	2265	411	18.1	11.8
[WH]	4809	398	8.3	7.5
[WI]	3511	371	10.6	10.1
[WJ]	4315	729	16.9	9.0
[WK]	1625	247	15.2	14.0
[WL]	1014	175	17.2	18.7

Note: Sample Size = 6

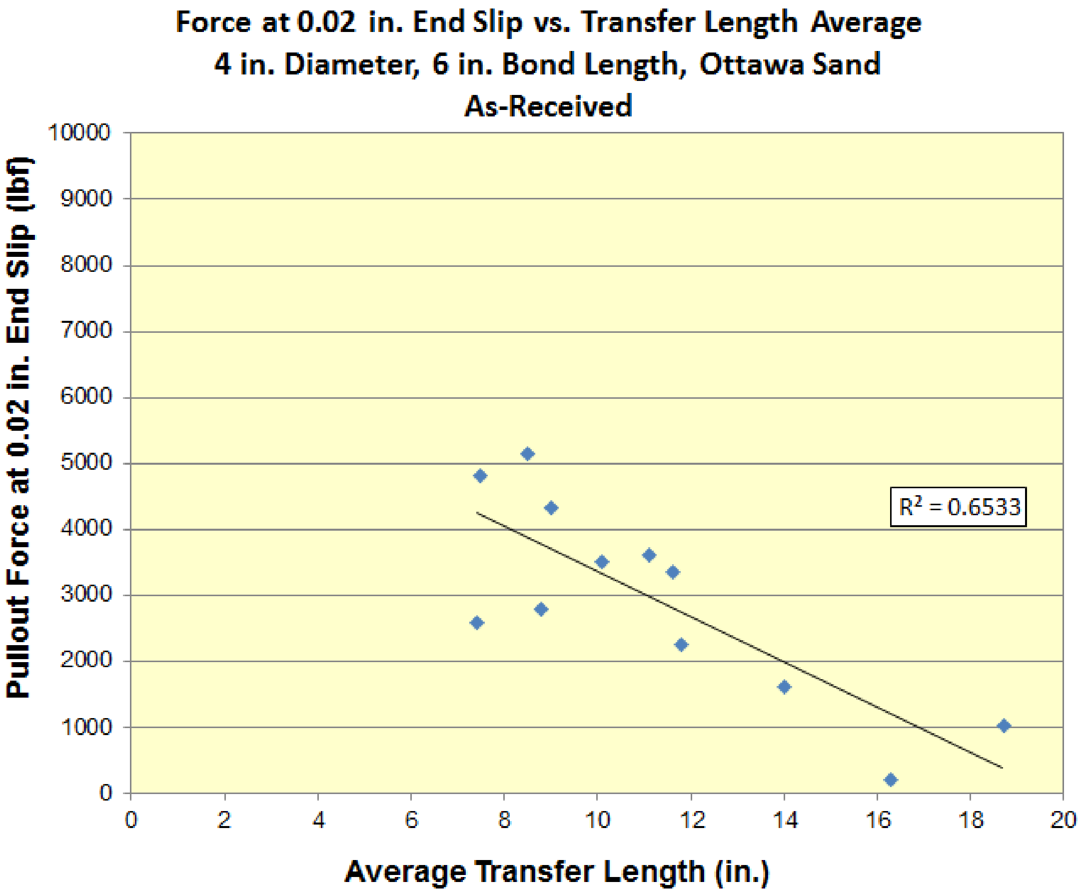


Figure F.3 As-received wires, pullout force at 0.02 in. end slip

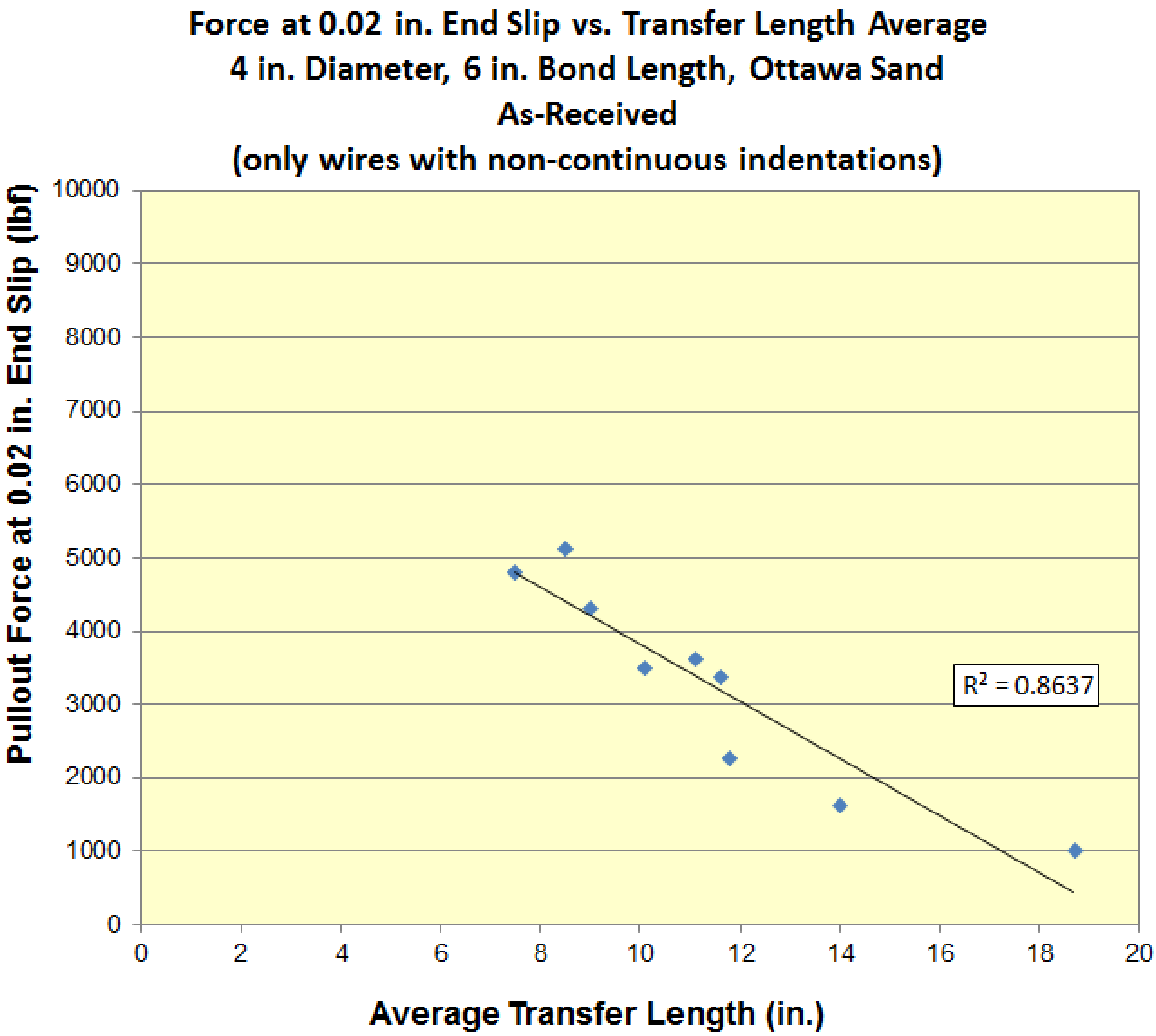
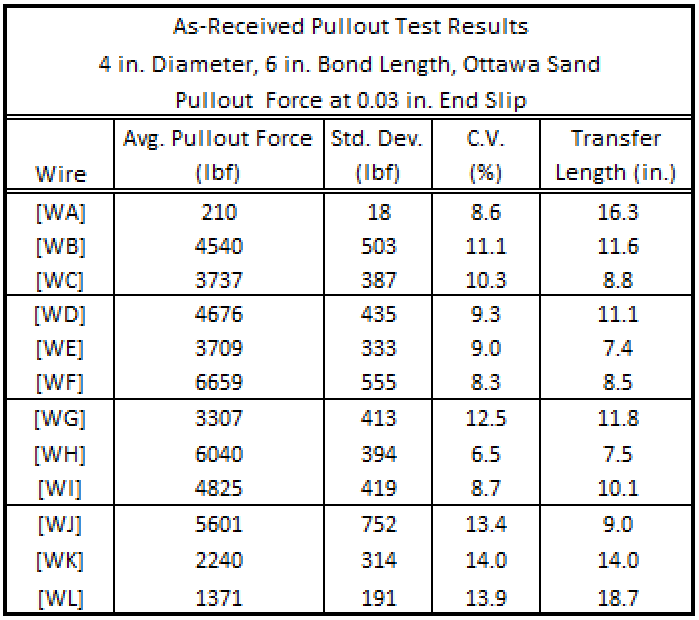


Figure F.4 As-received wires, pullout force at 0.02 in. end slip (individual-indents only)

Table F.3 As-received wires, pullout force at 0.03 in. end slip



As-Received Pullout Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Pullout Force at 0.03 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	210	18	8.6	16.3
[WB]	4540	503	11.1	11.6
[WC]	3737	387	10.3	8.8
[WD]	4676	435	9.3	11.1
[WE]	3709	333	9.0	7.4
[WF]	6659	555	8.3	8.5
[WG]	3307	413	12.5	11.8
[WH]	6040	394	6.5	7.5
[WI]	4825	419	8.7	10.1
[WJ]	5601	752	13.4	9.0
[WK]	2240	314	14.0	14.0
[WL]	1371	191	13.9	18.7

Note: Sample Size = 6

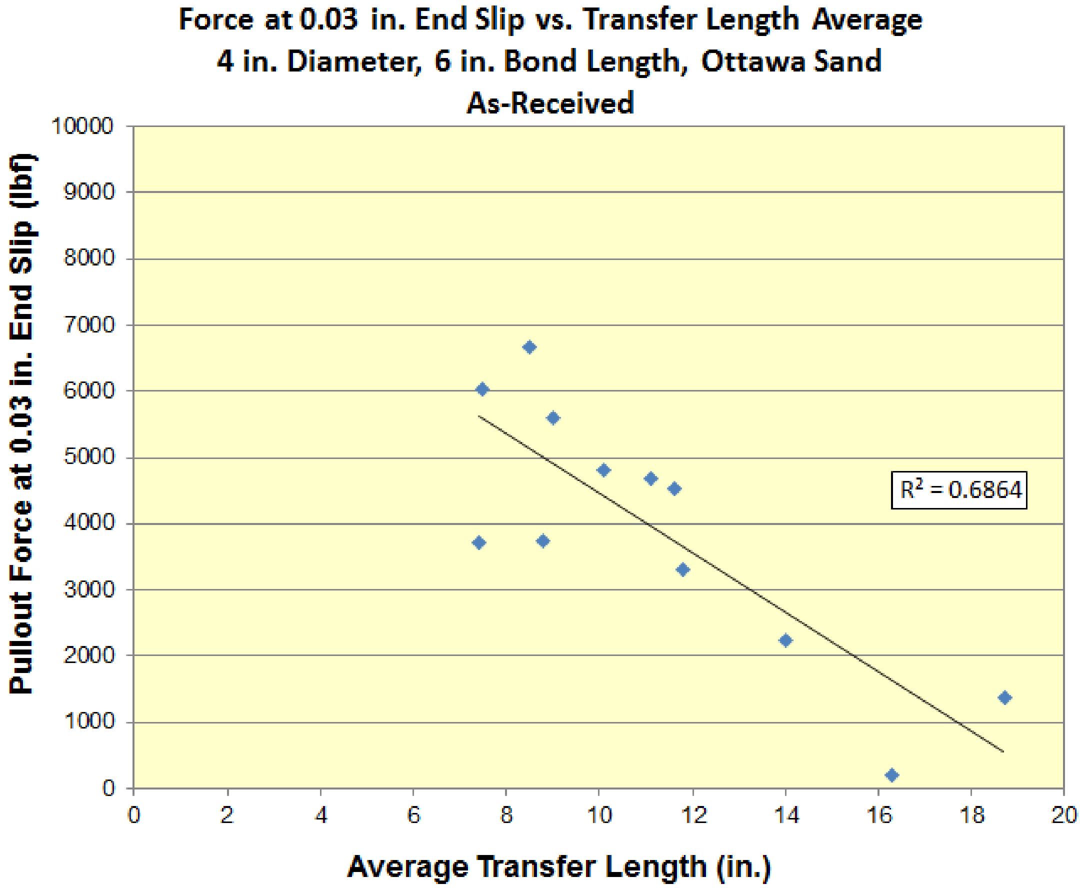


Figure F.5 As-received wires, pullout force at 0.03 in. end slip

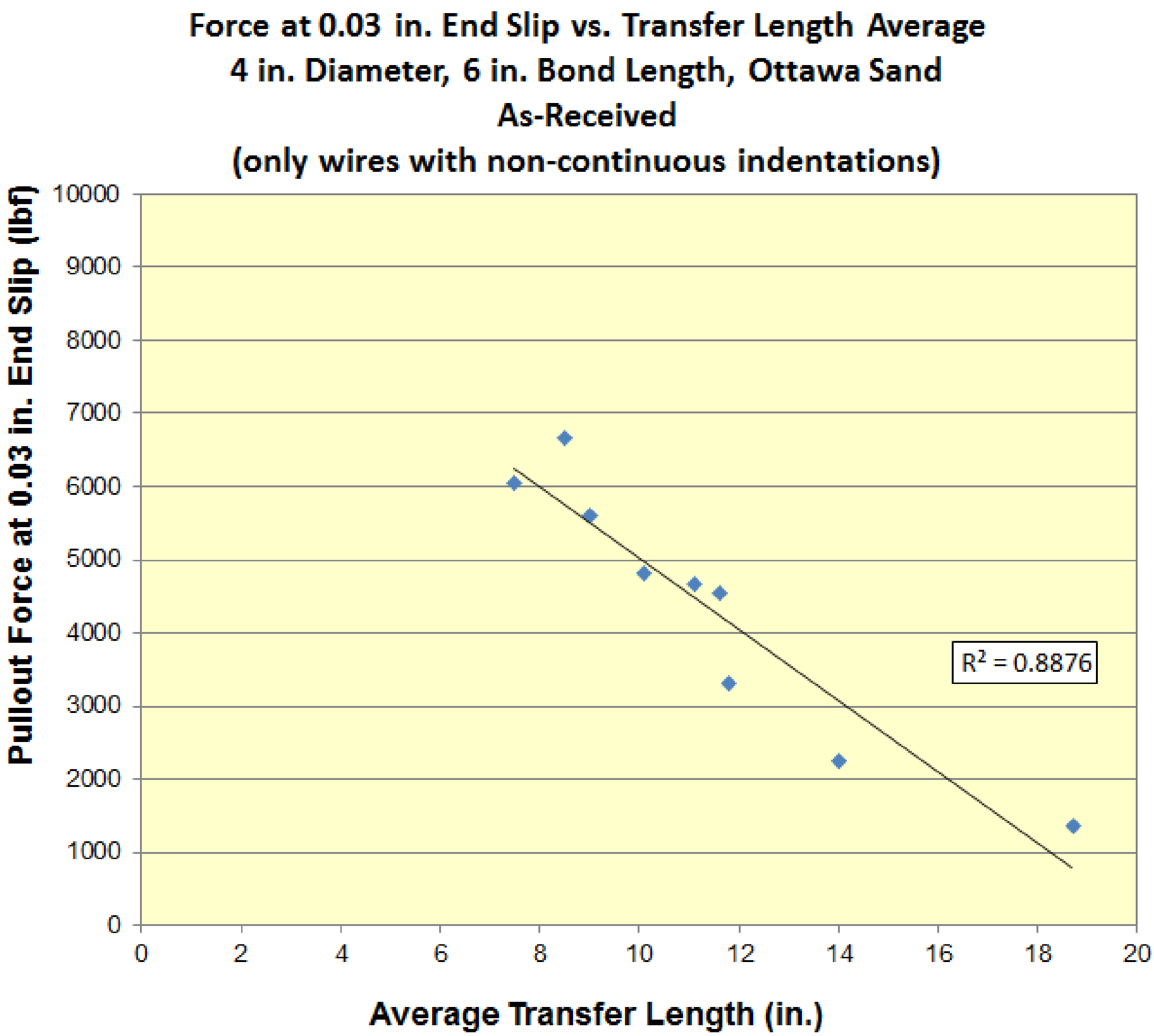


Figure F.6 As-received wires, pullout force at 0.03 in. end slip (individual-indents only)

Table F.4 As-received wires, pullout force at 0.04 in. end slip

As-Received Pullout Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
Pullout Force at 0.04 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	217	18	8.1	16.3
[WB]	5210	533	10.2	11.6
[WC]	4514	434	9.6	8.8
[WD]	5187	400	7.7	11.1
[WE]	4630	379	8.2	7.4
[WF]	7485	565	7.6	8.5
[WG]	4051	411	10.1	11.8
[WH]	6742	423	6.3	7.5
[WI]	5603	468	8.4	10.1
[WJ]	6291	728	11.6	9.0
[WK]	2653	333	12.5	14.0
[WL]	1614	219	13.6	18.7

Note: Sample Size = 6

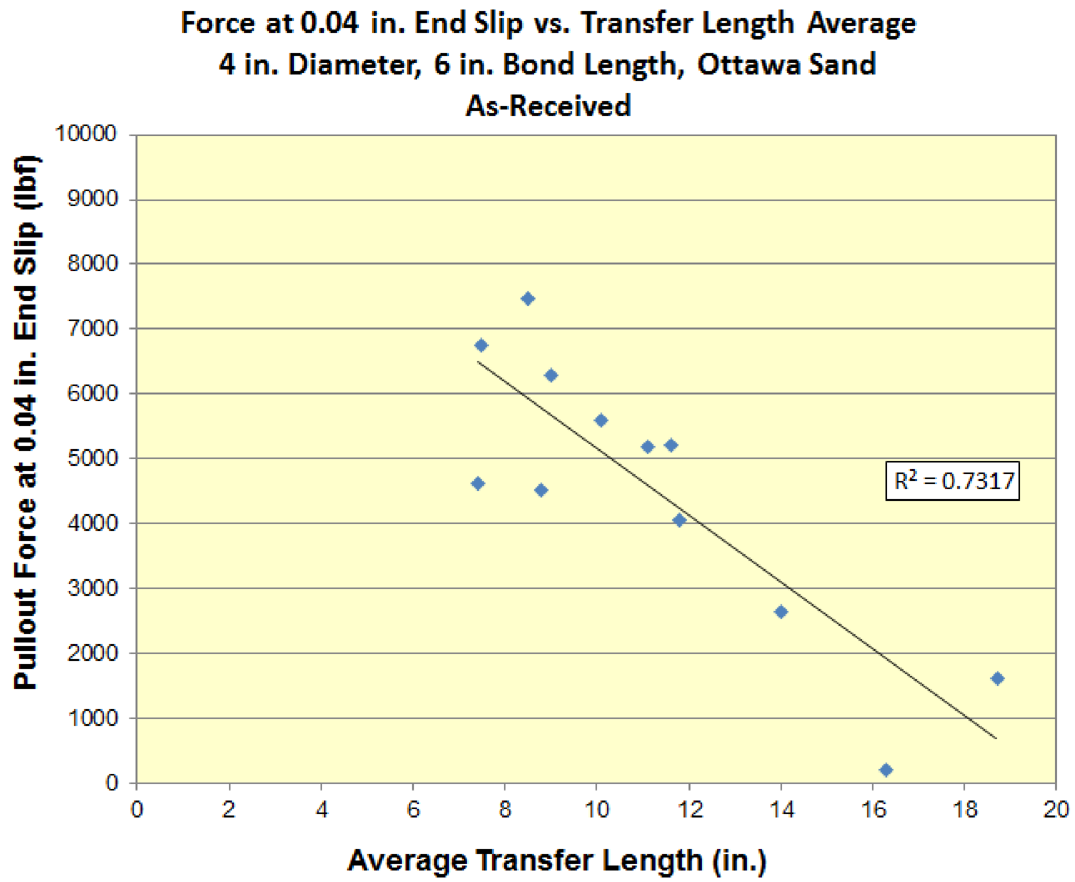


Figure F.7 As-received wires, pullout force at 0.04 in. end slip

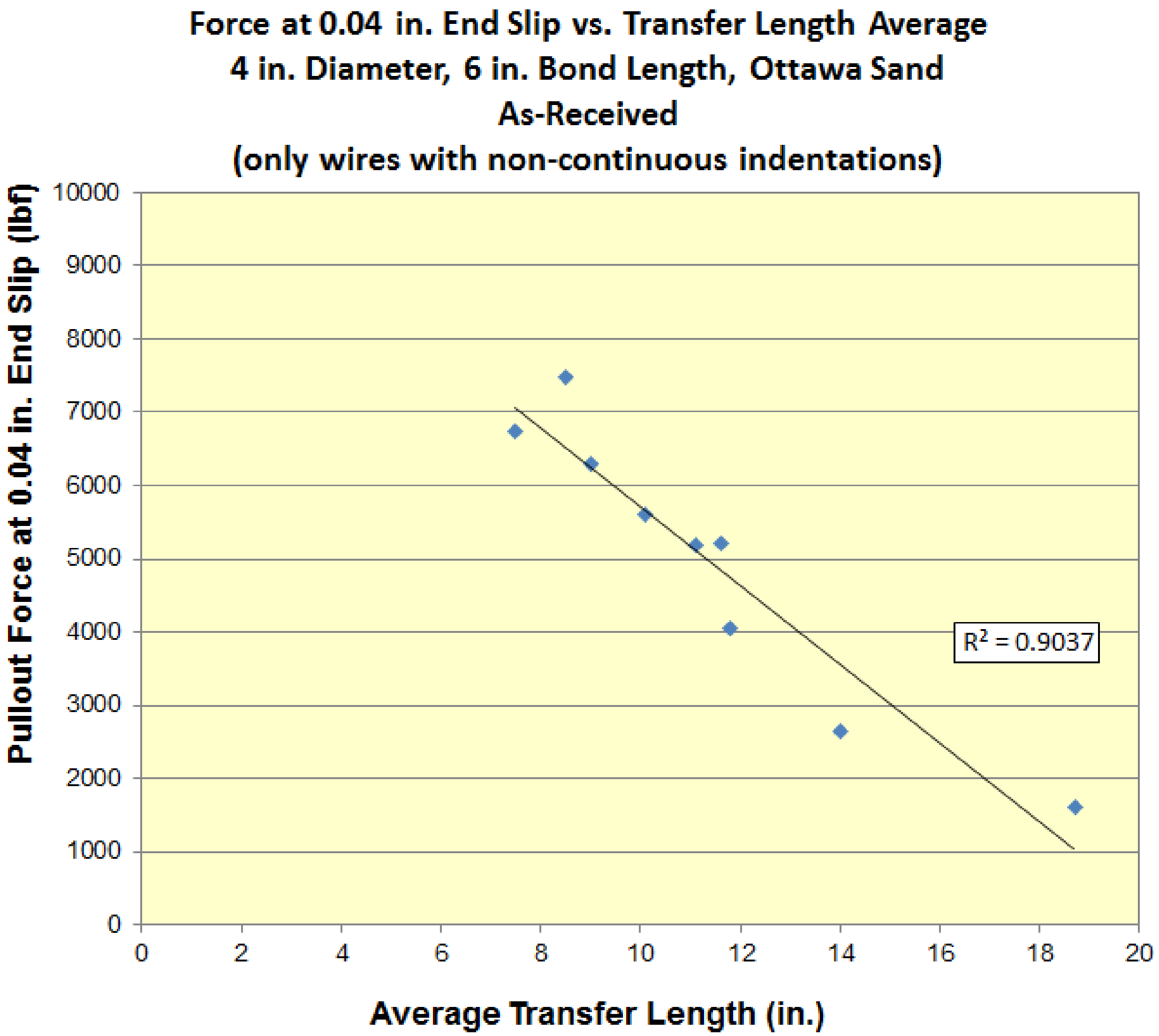


Figure F.8 As-received wires, pullout force at 0.04 in. end slip (individual-indents only)

Table F.5 As-received wires, pullout force at 0.05 in. end slip

As-Received Pullout Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
Pullout Force at 0.05 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	234	20	8.6	16.3
[WB]	5627	592	10.5	11.6
[WC]	5198	499	9.6	8.8
[WD]	5400	391	7.2	11.1
[WE]	5381	402	7.5	7.4
[WF]	7928	535	6.8	8.5
[WG]	4586	407	8.9	11.8
[WH]	7186	488	6.8	7.5
[WI]	6095	506	8.3	10.1
[WJ]	6682	687	10.3	9.0
[WK]	2919	306	10.5	14.0
[WL]	1773	260	14.7	18.7

Note: Sample Size = 6

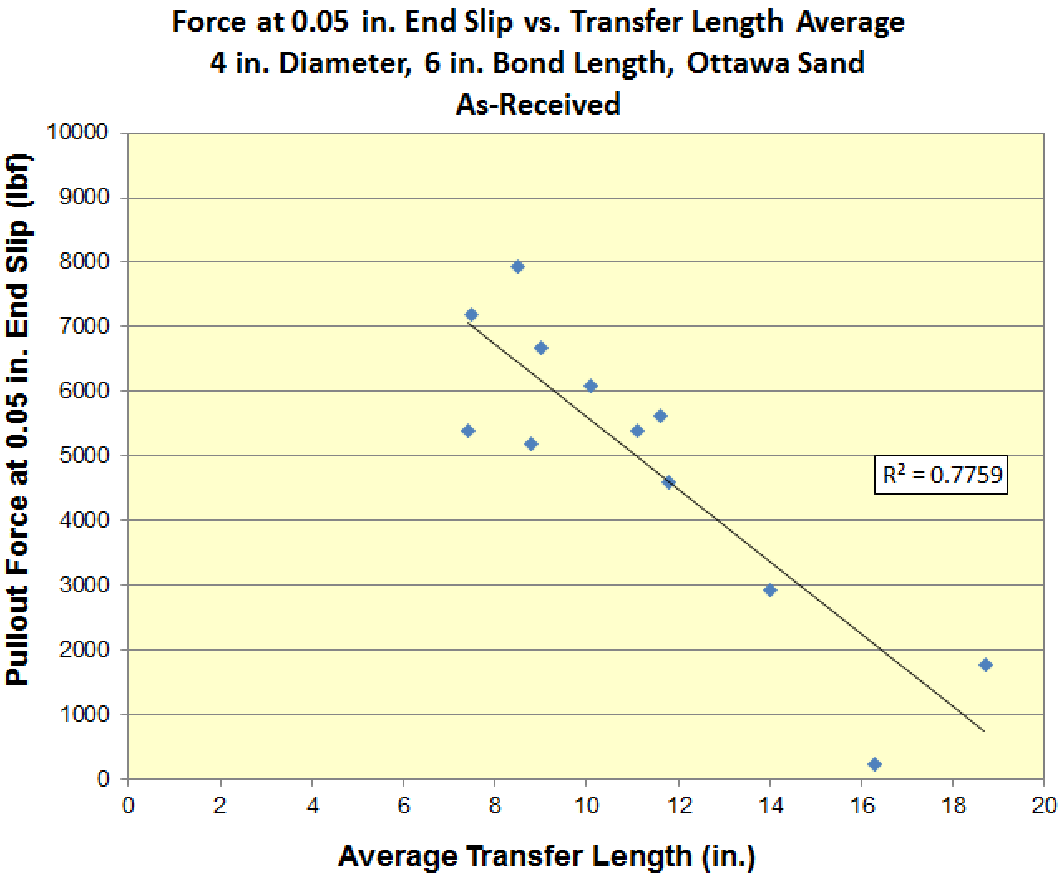


Figure F.9 As-received wires, pullout force at 0.05 in. end slip

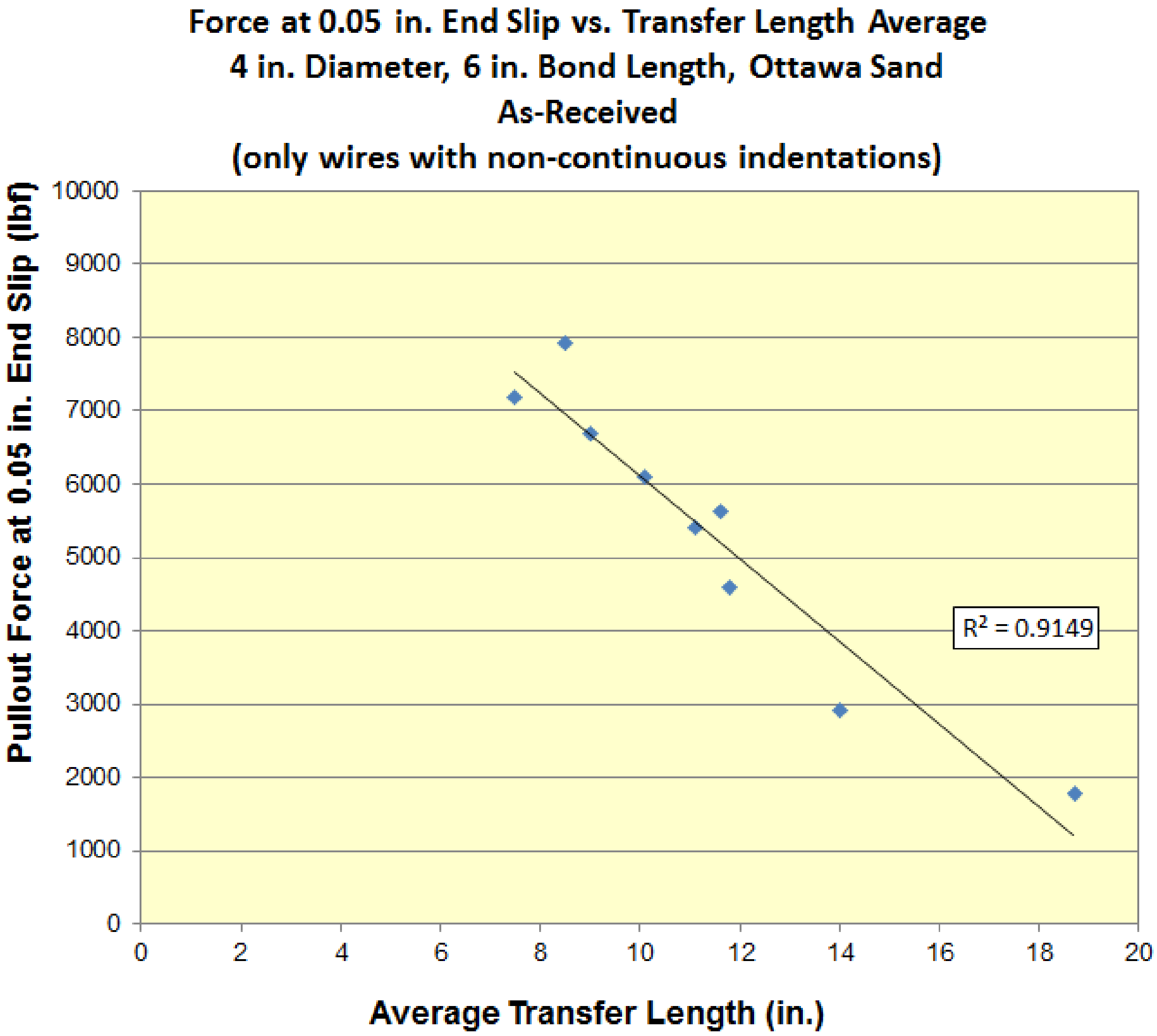


Figure F.10 As-received wires, pullout force at 0.05 in. end slip (individual-indents only)

Table F.6 As-received wires, pullout force at 0.06 in. end slip

As-Received Pullout Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
Pullout Force at 0.06 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	255	24	9.2	16.3
[WB]	5936	624	10.5	11.6
[WC]	5785	570	9.8	8.8
[WD]	5494	378	6.9	11.1
[WE]	6018	434	7.2	7.4
[WF]	8192	491	6.0	8.5
[WG]	4972	400	8.1	11.8
[WH]	7458	508	6.8	7.5
[WI]	6372	520	8.2	10.1
[WJ]	6899	664	9.6	9.0
[WK]	3111	320	10.3	14.0
[WL]	1878	289	15.4	18.7

Note: Sample Size = 6

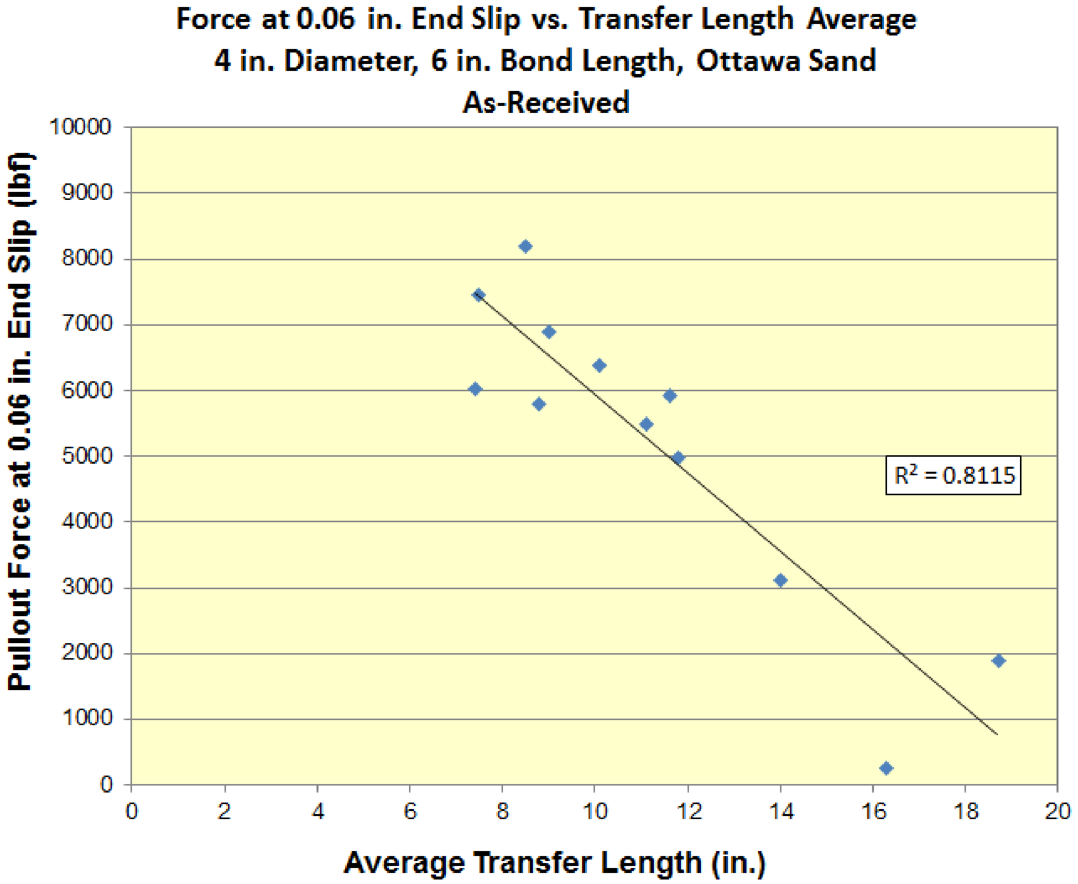


Figure F.11 As-received wires, pullout force at 0.06 in. end slip

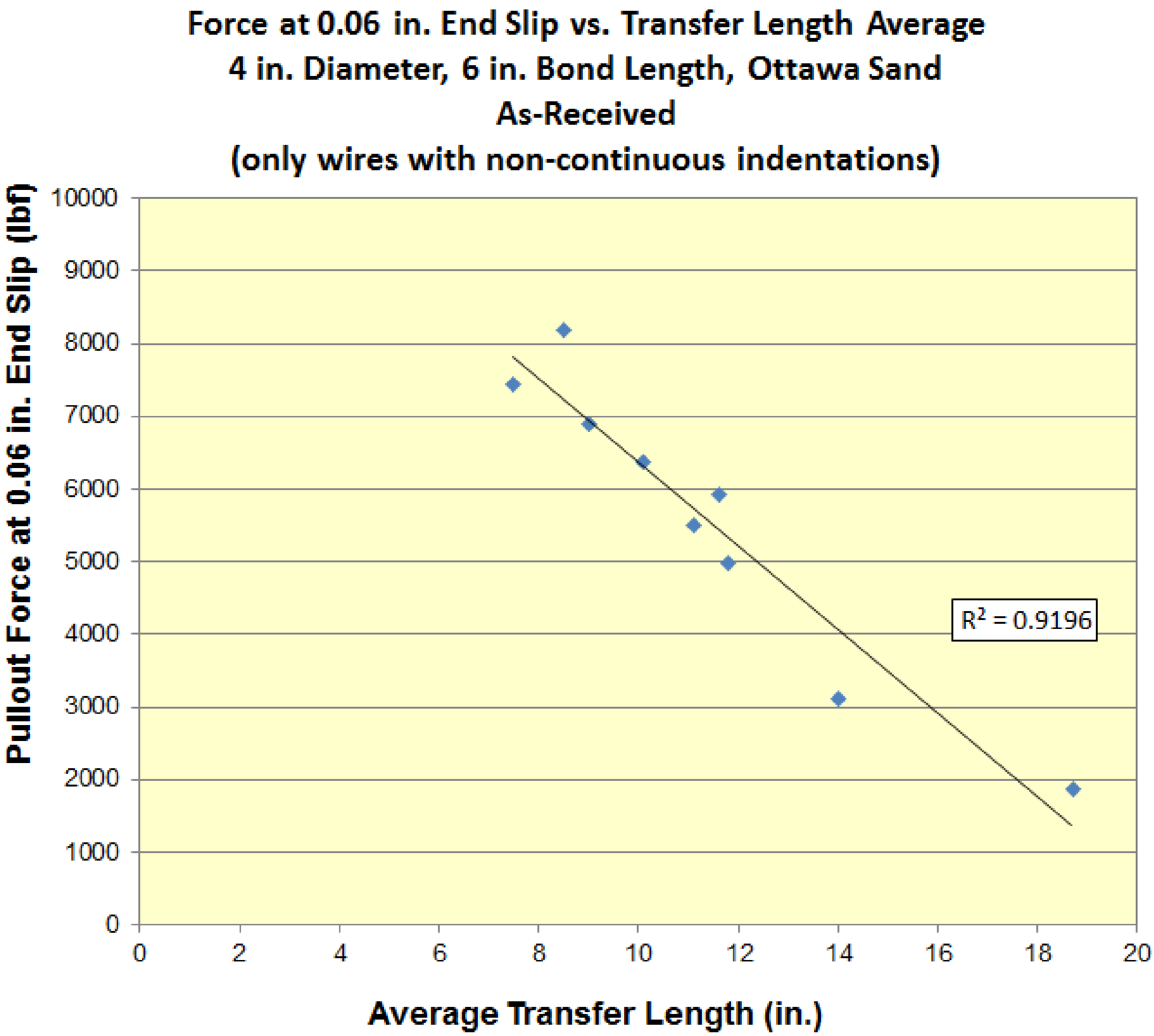


Figure F.12 As-received wires, pullout force at 0.06 in. end slip (individual-indents only)

Table F.7 As-received wires, pullout force at 0.07 in. end slip

As-Received Pullout Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
Pullout Force at 0.07 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	282	27	9.4	16.3
[WB]	6178	621	10.1	11.6
[WC]	6358	671	10.5	8.8
[WD]	5534	355	6.4	11.1
[WE]	6547	468	7.2	7.4
[WF]	8296	464	5.6	8.5
[WG]	5269	398	7.6	11.8
[WH]	7585	508	6.7	7.5
[WI]	6514	525	8.1	10.1
[WJ]	7009	645	9.2	9.0
[WK]	3227	322	10.0	14.0
[WL]	1951	311	15.9	18.7

Note: Sample Size = 6

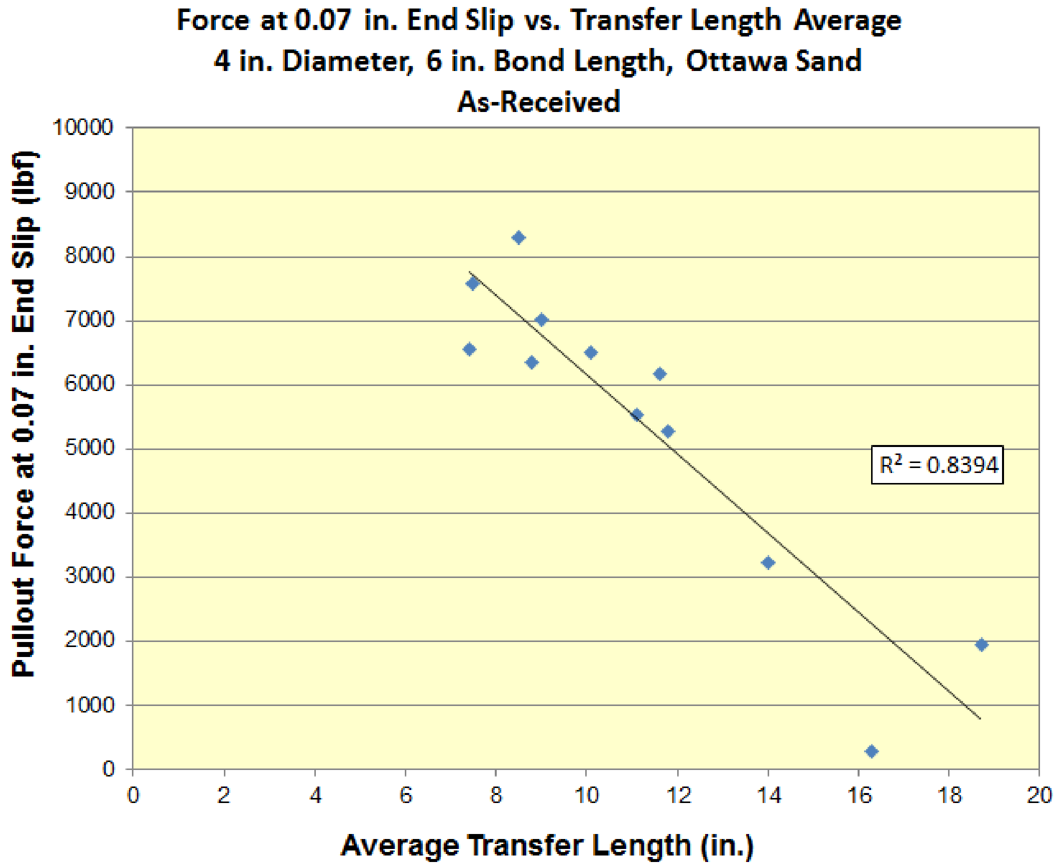


Figure F.13 As-received wires, pullout force at 0.07 in. end slip

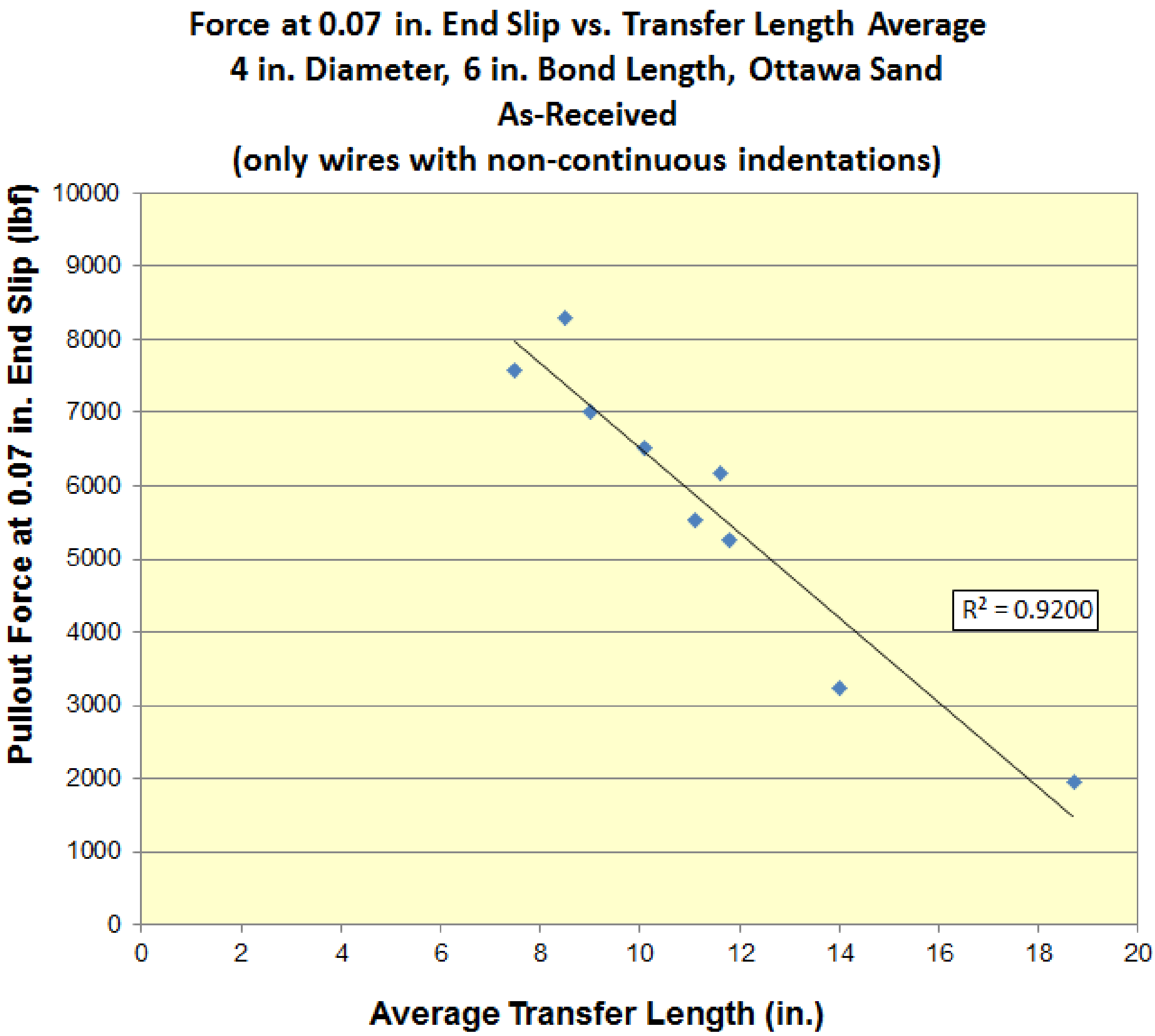


Figure F.14 As-received wires, pullout force at 0.07 in. end slip (individual-indents only)

Table F.8 As-received wires, pullout force at 0.08 in. end slip

As-Received Pullout Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
Pullout Force at 0.08 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	311	29	9.2	16.3
[WB]	6356	607	9.6	11.6
[WC]	6860	794	11.6	8.8
[WD]	5511	333	6.0	11.1
[WE]	6983	474	6.8	7.4
[WF]	8287	453	5.5	8.5
[WG]	5440	388	7.1	11.8
[WH]	7588	497	6.5	7.5
[WI]	6558	525	8.0	10.1
[WJ]	7025	628	8.9	9.0
[WK]	3324	348	10.5	14.0
[WL]	1999	318	15.9	18.7

Note: Sample Size = 6

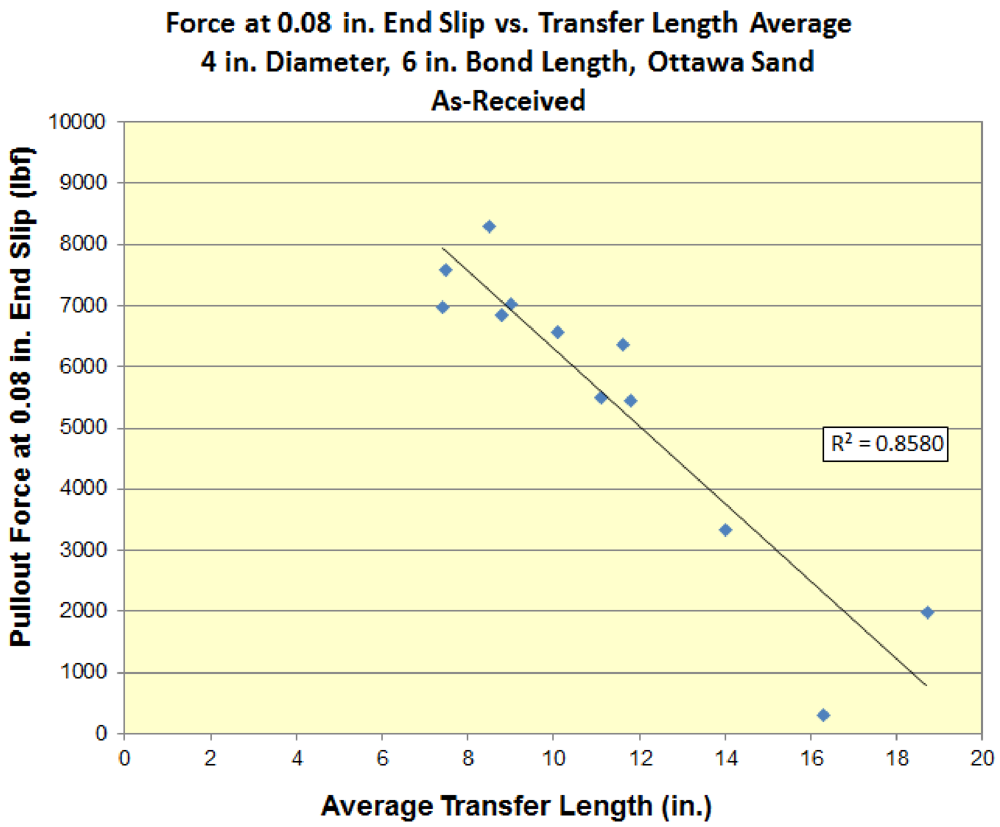


Figure F.15 As-received wires, pullout force at 0.08 in. end slip

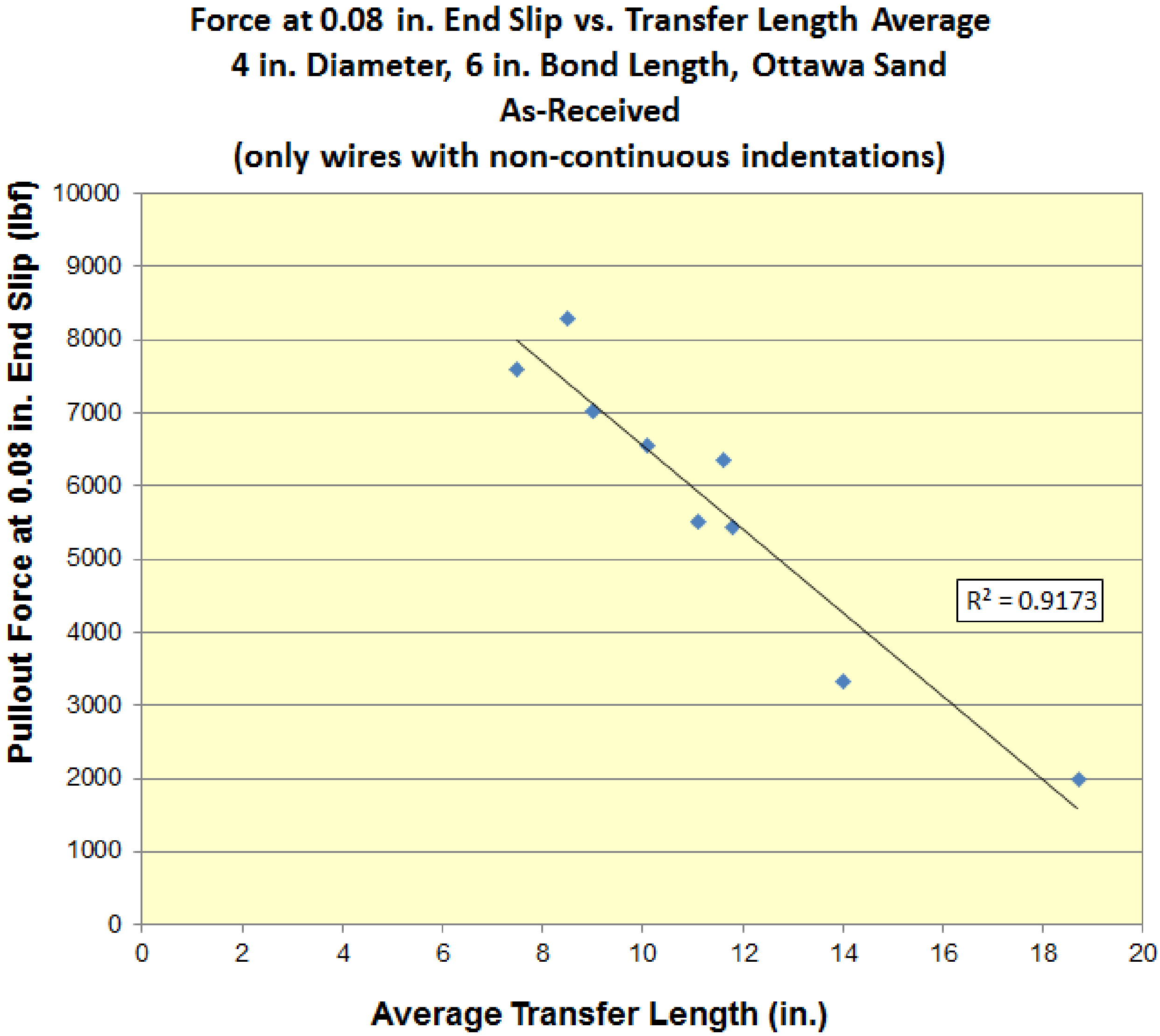
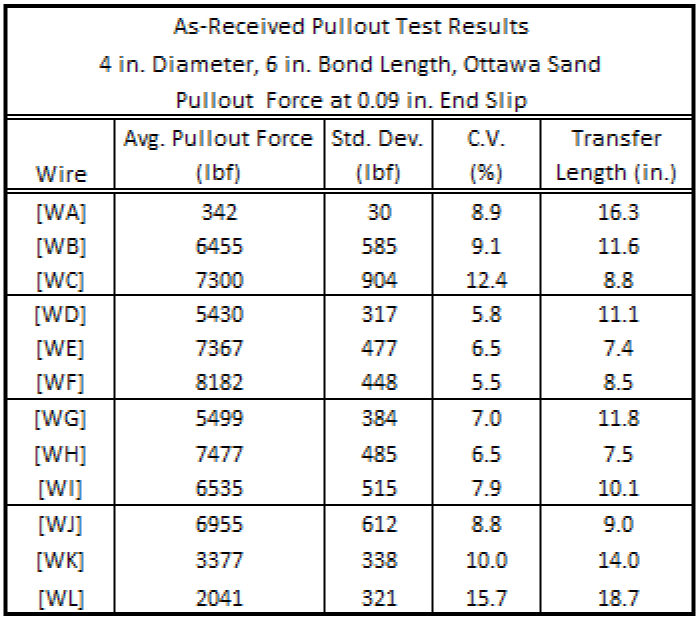


Figure F.16 As-received wires, pullout force at 0.08 in. end slip (individual-indents only)

Table F.9 As-received wires, pullout force at 0.09 in. end slip



As-Received Pullout Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
Pullout Force at 0.09 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	342	30	8.9	16.3
[WB]	6455	585	9.1	11.6
[WC]	7300	904	12.4	8.8
[WD]	5430	317	5.8	11.1
[WE]	7367	477	6.5	7.4
[WF]	8182	448	5.5	8.5
[WG]	5499	384	7.0	11.8
[WH]	7477	485	6.5	7.5
[WI]	6535	515	7.9	10.1
[WJ]	6955	612	8.8	9.0
[WK]	3377	338	10.0	14.0
[WL]	2041	321	15.7	18.7

Note: Sample Size = 6

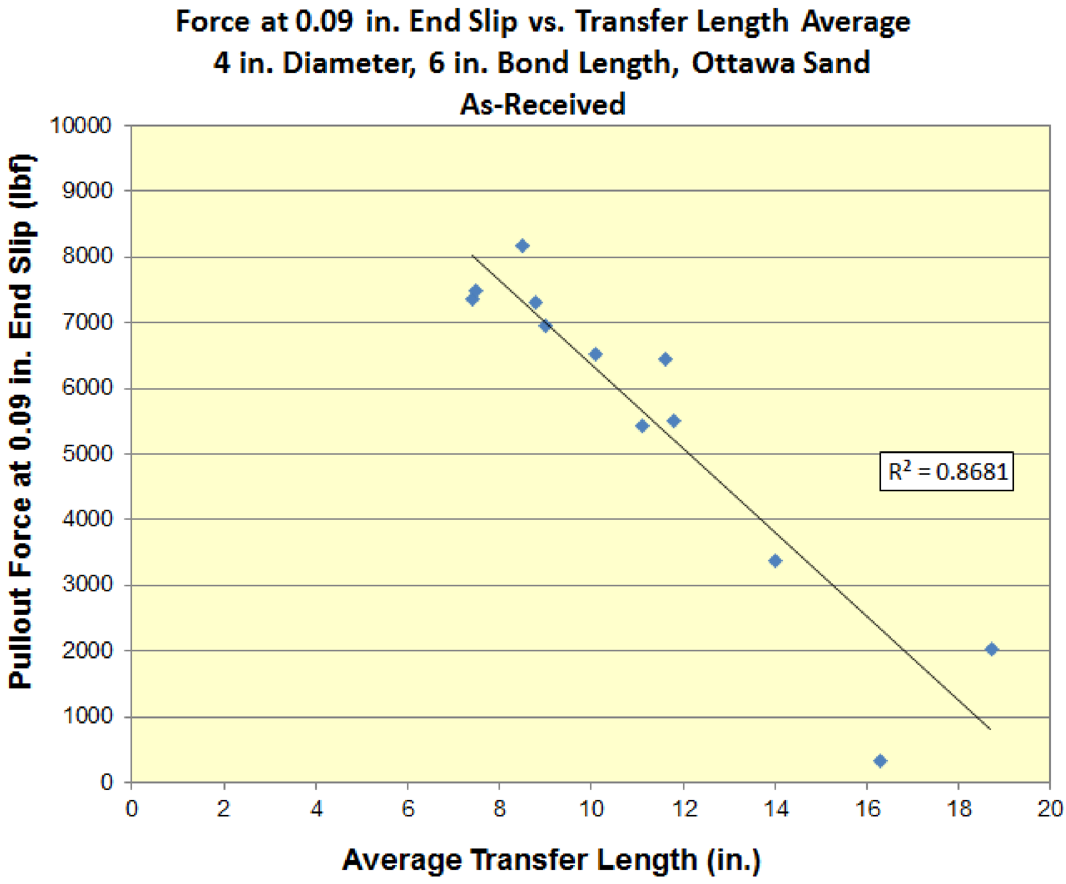


Figure F.17 As-received wires, pullout force at 0.09 in. end slip

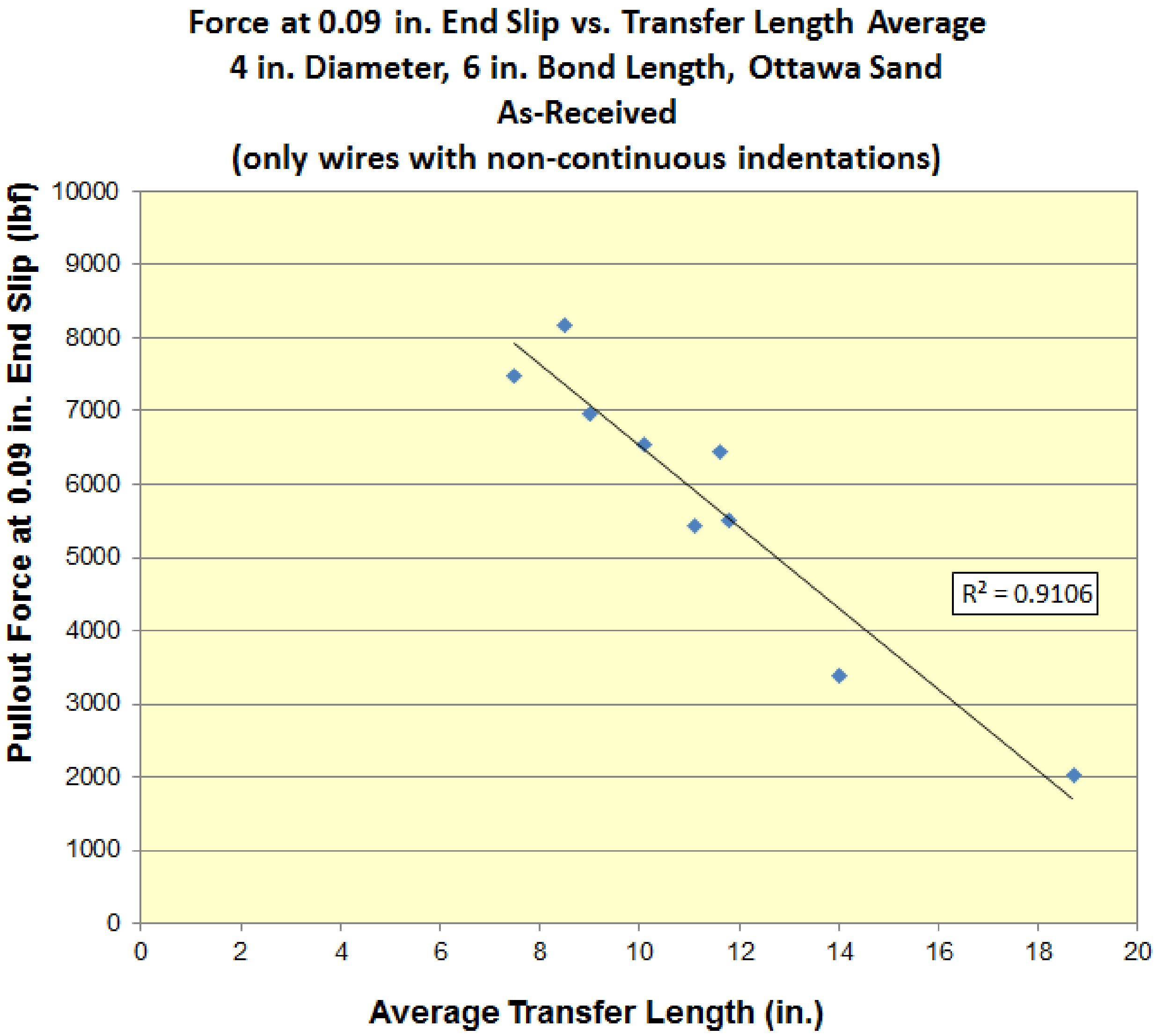


Figure F.18 As-received wires, pullout force at 0.09 in. end slip (individual-indents only)

Table F.10 As-received wires, pullout force at 0.10 in. end slip

As-Received Pullout Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
Pullout Force at 0.10 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	378	32	8.5	16.3
[WB]	6473	563	8.7	11.6
[WC]	7663	969	12.6	8.8
[WD]	5302	300	5.7	11.1
[WE]	7817	487	6.2	7.4
[WF]	7993	441	5.5	8.5
[WG]	5469	388	7.1	11.8
[WH]	7270	462	6.4	7.5
[WI]	6439	498	7.7	10.1
[WJ]	6814	591	8.7	9.0
[WK]	3434	347	10.1	14.0
[WL]	2067	323	15.6	18.7

Note: Sample Size = 6, WE = 5

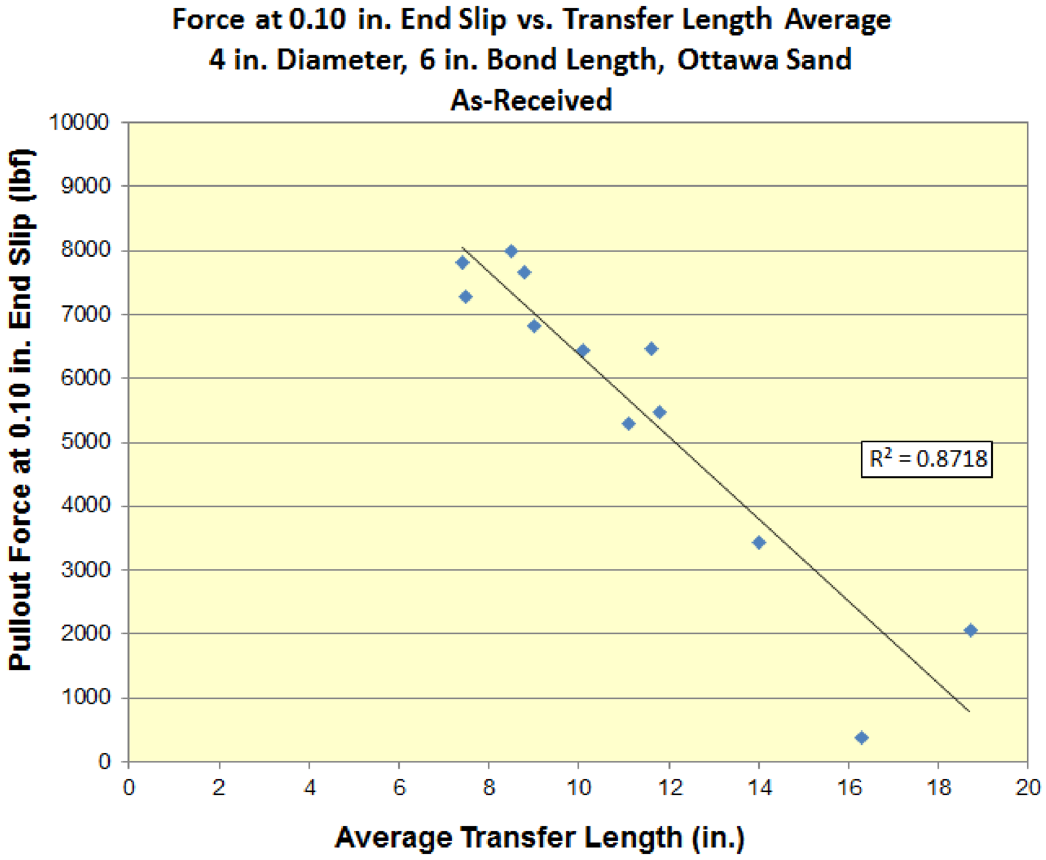


Figure F.19 As-received wires, pullout force at 0.10 in. end slip

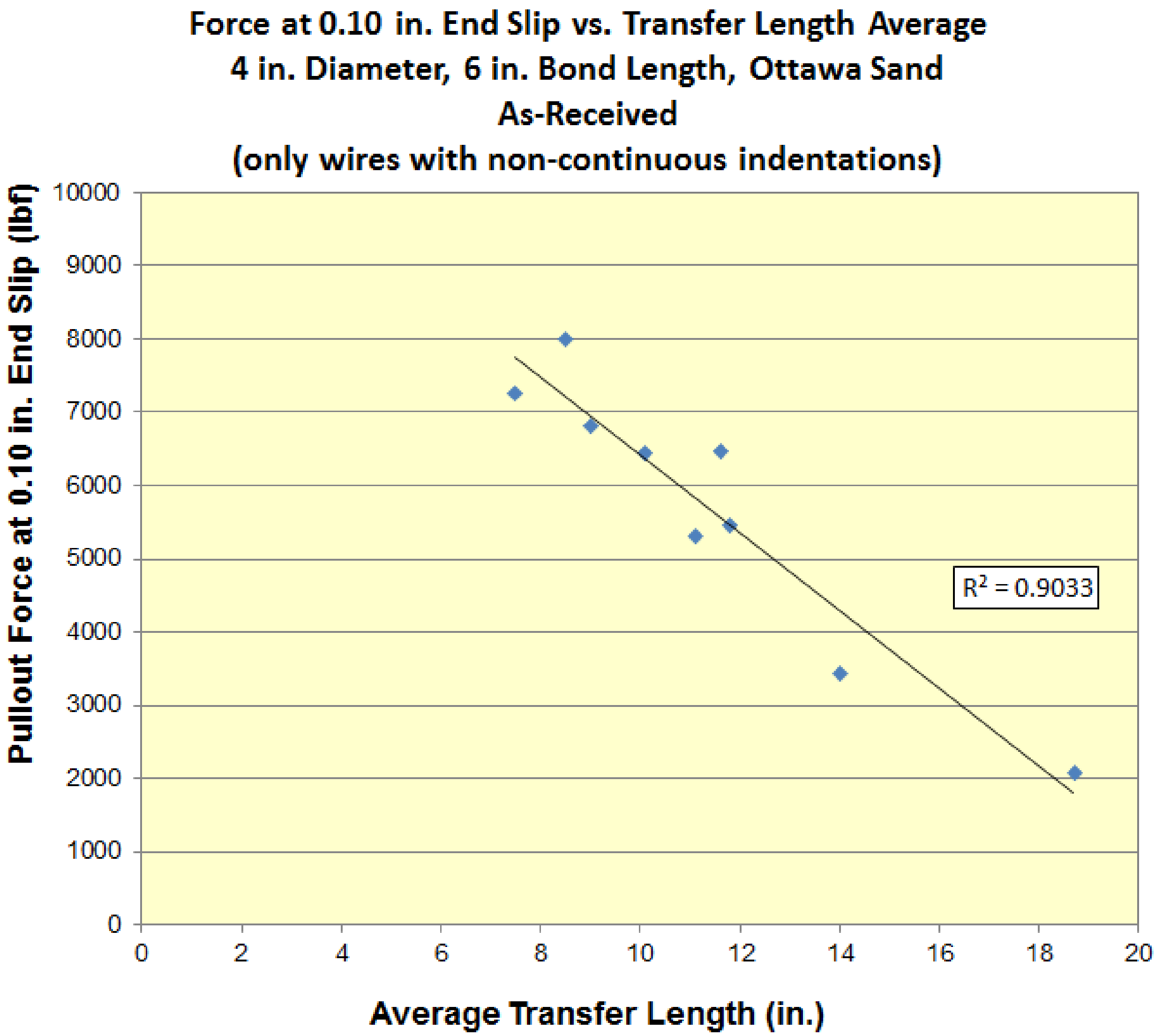


Figure F.20 As-received wires, pullout force at 0.10 in. end slip (individual-indents only)

Table F.11 As-received wires, pullout force at 0.11 in. end slip

As-Received Pullout Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Pullout Force at 0.11 in. End Slip				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	415	33	8.0	16.3
[WB]	6399	544	8.5	11.6
[WC]	7958	997	12.5	8.8
[WD]	5129	289	5.6	11.1
[WE]	8138	539	6.6	7.4
[WF]	7761	436	5.6	8.5
[WG]	5367	394	7.3	11.8
[WH]	6976	427	6.1	7.5
[WI]	6280	467	7.4	10.1
[WJ]	6592	558	8.5	9.0
[WK]	3460	375	10.8	14.0
[WL]	2091	323	15.4	18.7

Note: Sample Size = 6, WE = 5

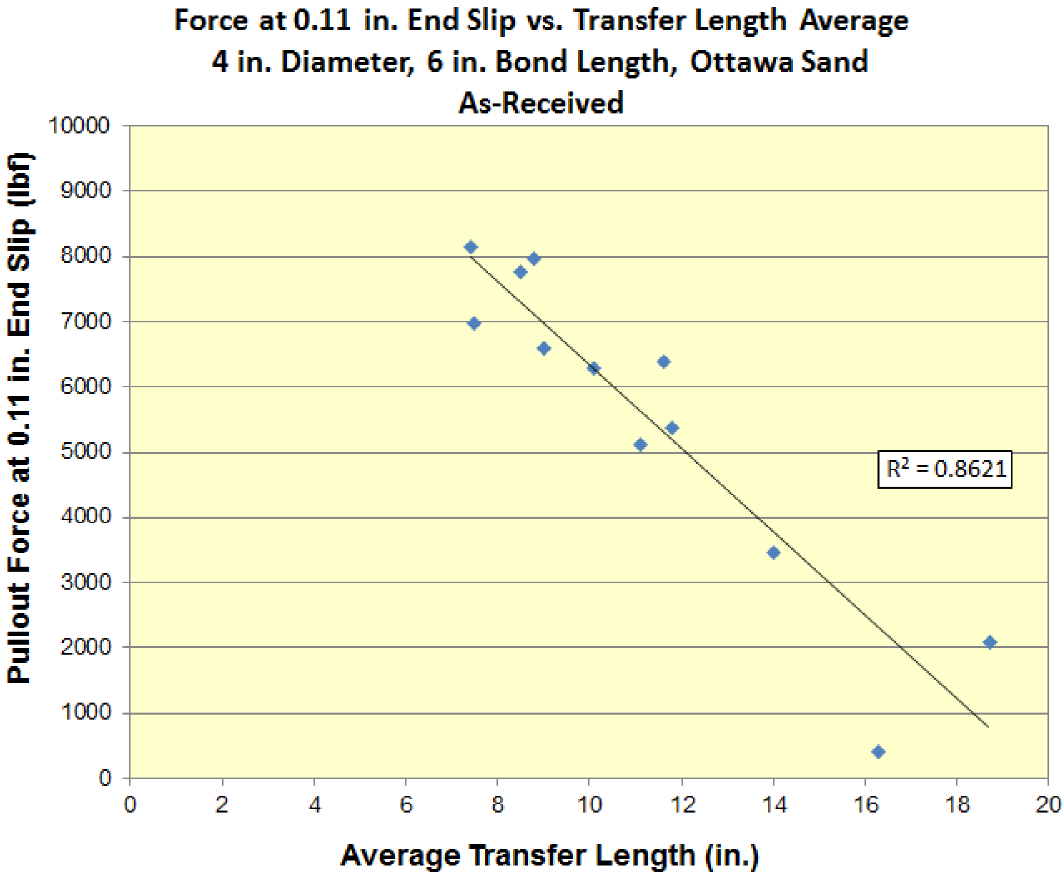


Figure F.21 As-received wires, pullout force at 0.11 in. end slip

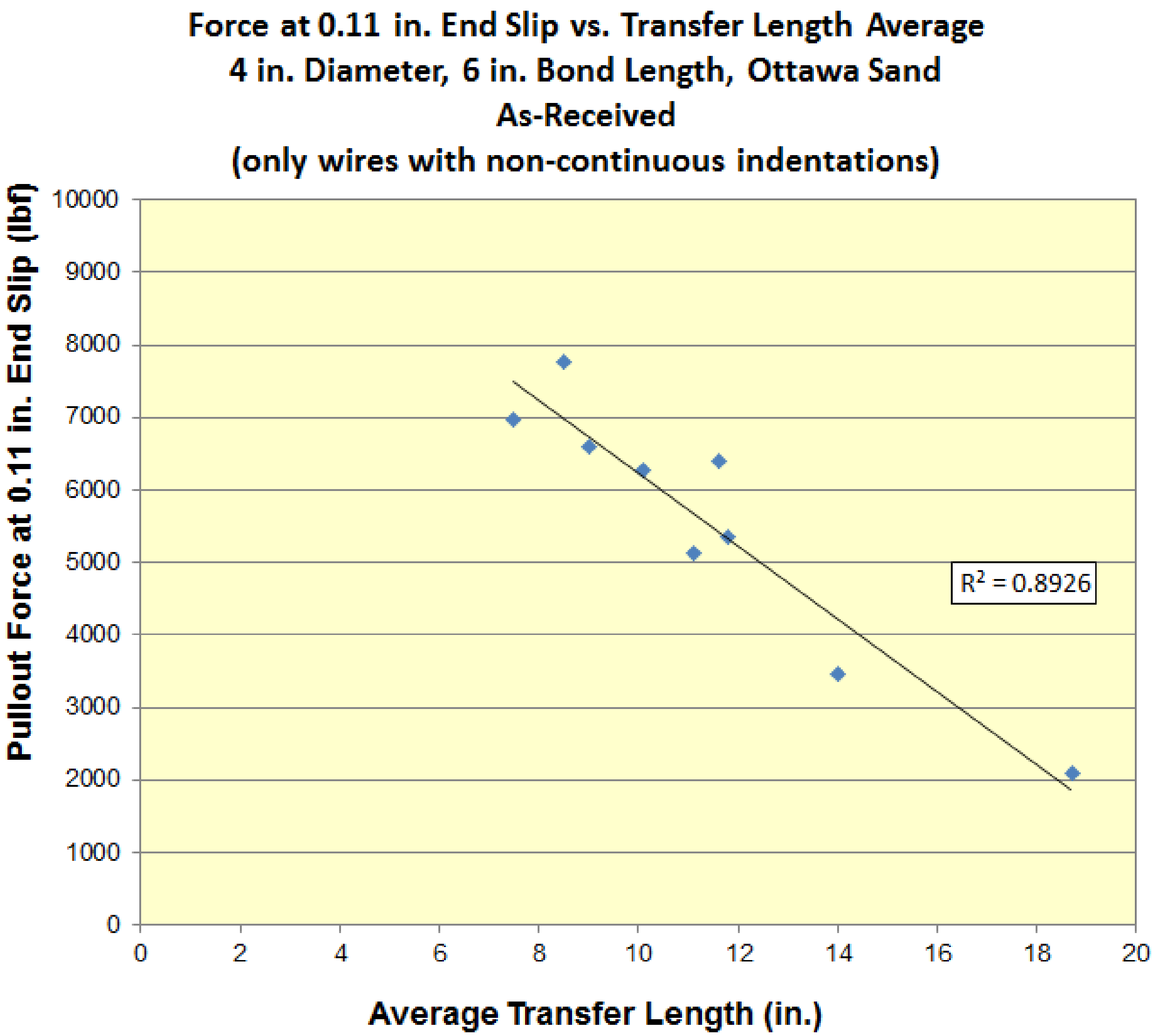


Figure F.22 As-received wires, pullout force at 0.11 in. end slip (individual-indents only)

Table F.12 As-received wires, pullout force at 0.12 in. end slip

As-Received Pullout Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
Pullout Force at 0.12 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	452	35	7.7	16.3
[WB]	6212	514	8.3	11.6
[WC]	7623	681	8.9	8.8
[WD]	4936	280	5.7	11.1
[WE]	8438	563	6.7	7.4
[WF]	7502	443	5.9	8.5
[WG]	5181	410	7.9	11.8
[WH]	6646	395	5.9	7.5
[WI]	6045	446	7.4	10.1
[WJ]	6315	523	8.3	9.0
[WK]	3488	382	10.9	14.0
[WL]	2114	319	15.1	18.7

Note: Sample Size = 6, WC = 4, WE = 5

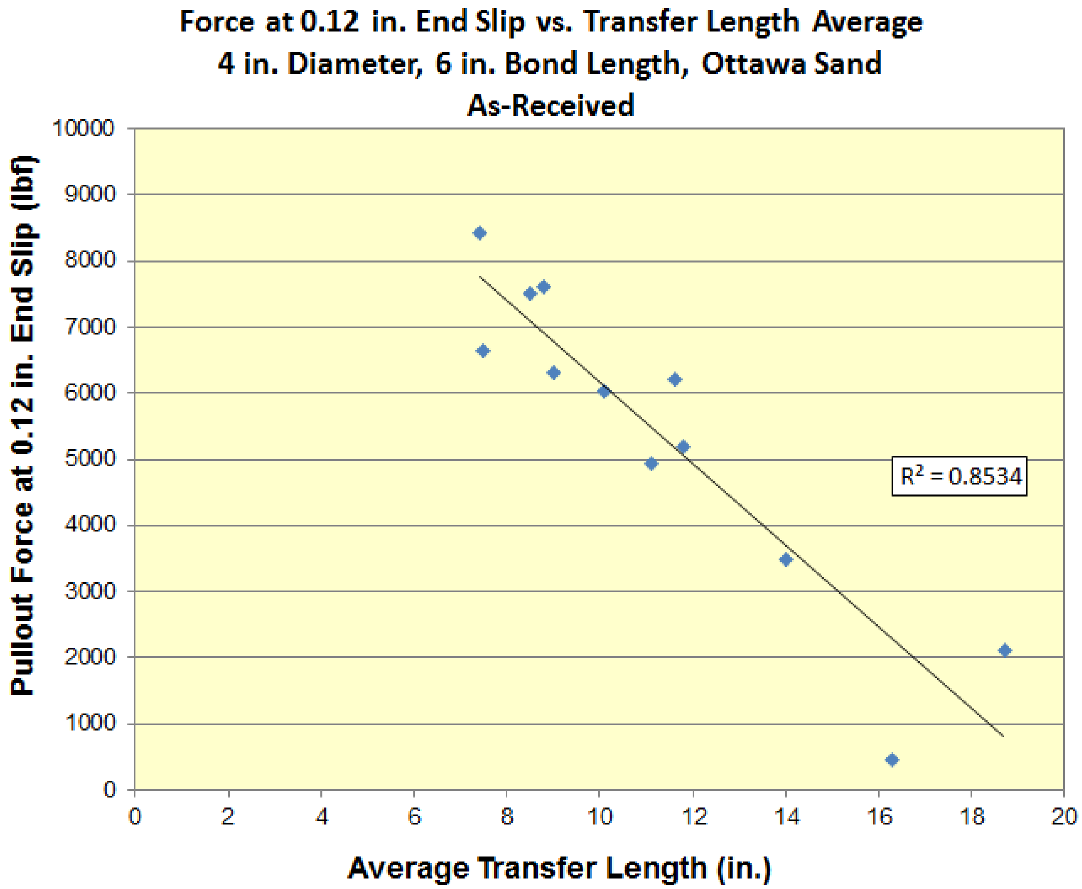


Figure F.23 As-received wires, pullout force at 0.12 in. end slip

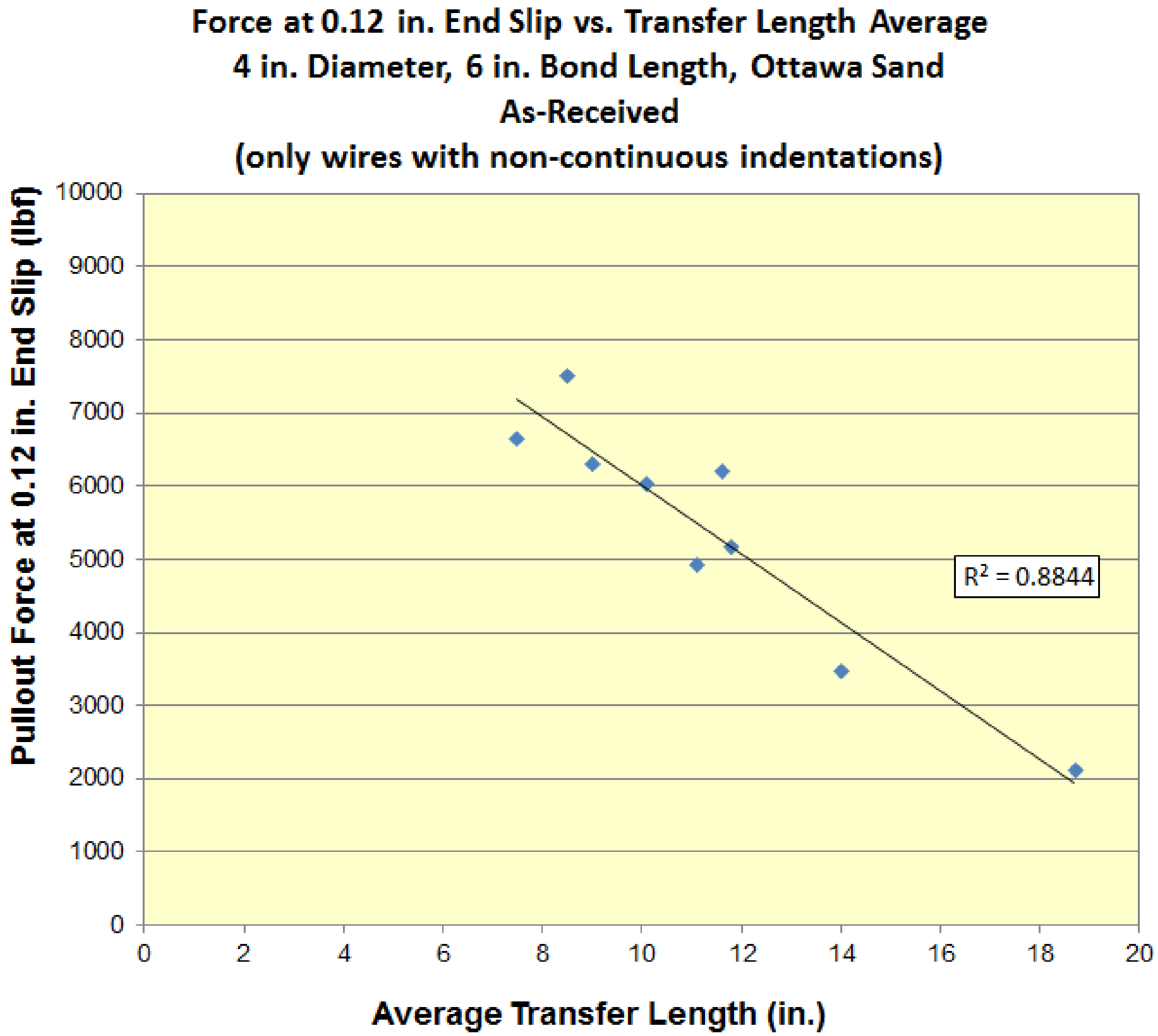


Figure F.24 As-received wires, pullout force at 0.12 in. end slip (individual-indents only)

Table F.13 As-received wires, pullout force at 0.13 in. end slip

As-Received Pullout Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
Pullout Force at 0.13 in. End Slip

Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	485	39	8.0	16.3
[WB]	5949	477	8.0	11.6
[WC]	7835	647	8.3	8.8
[WD]	4714	261	5.5	11.1
[WE]	8659	532	6.1	7.4
[WF]	7225	441	6.1	8.5
[WG]	4925	420	8.5	11.8
[WH]	6310	352	5.6	7.5
[WI]	5724	419	7.3	10.1
[WJ]	6004	478	8.0	9.0
[WK]	3506	394	11.2	14.0
[WL]	2119	315	14.9	18.7

Note: Sample Size = 6, WC = 4, WE = 5

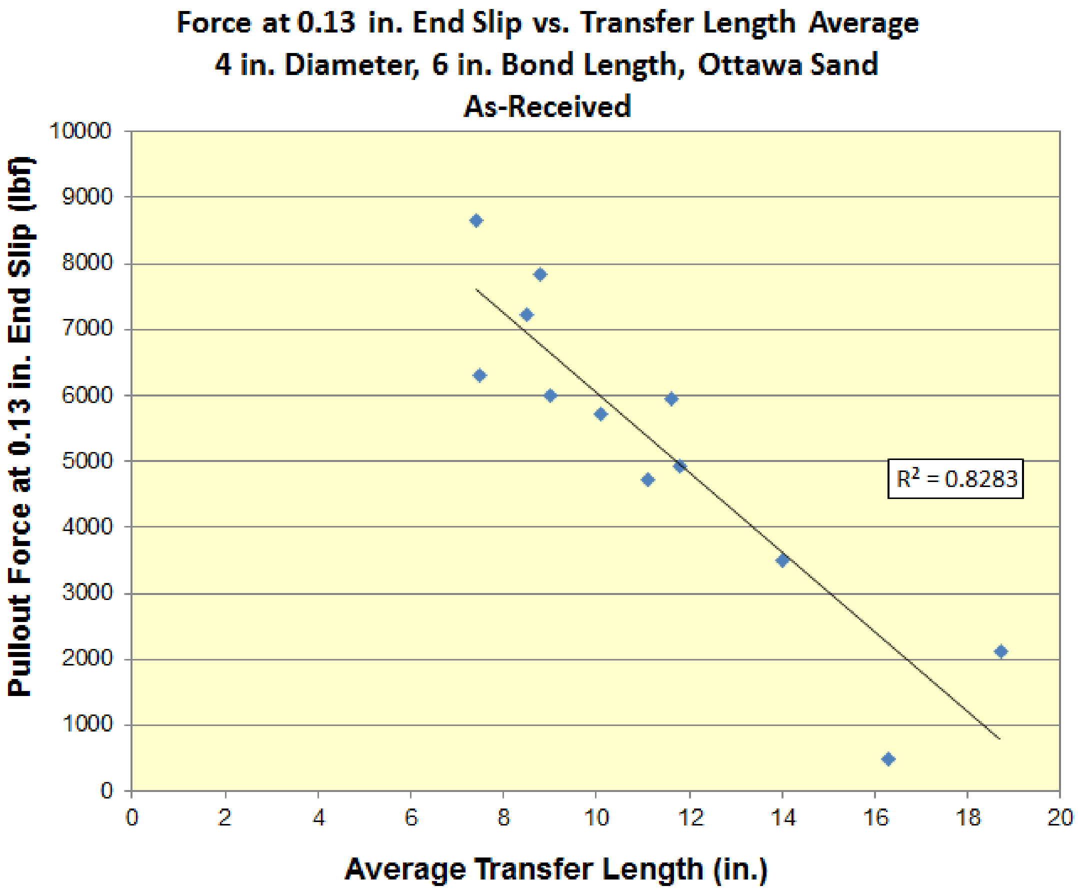


Figure F.25 As-received wires, pullout force at 0.13 in. end slip

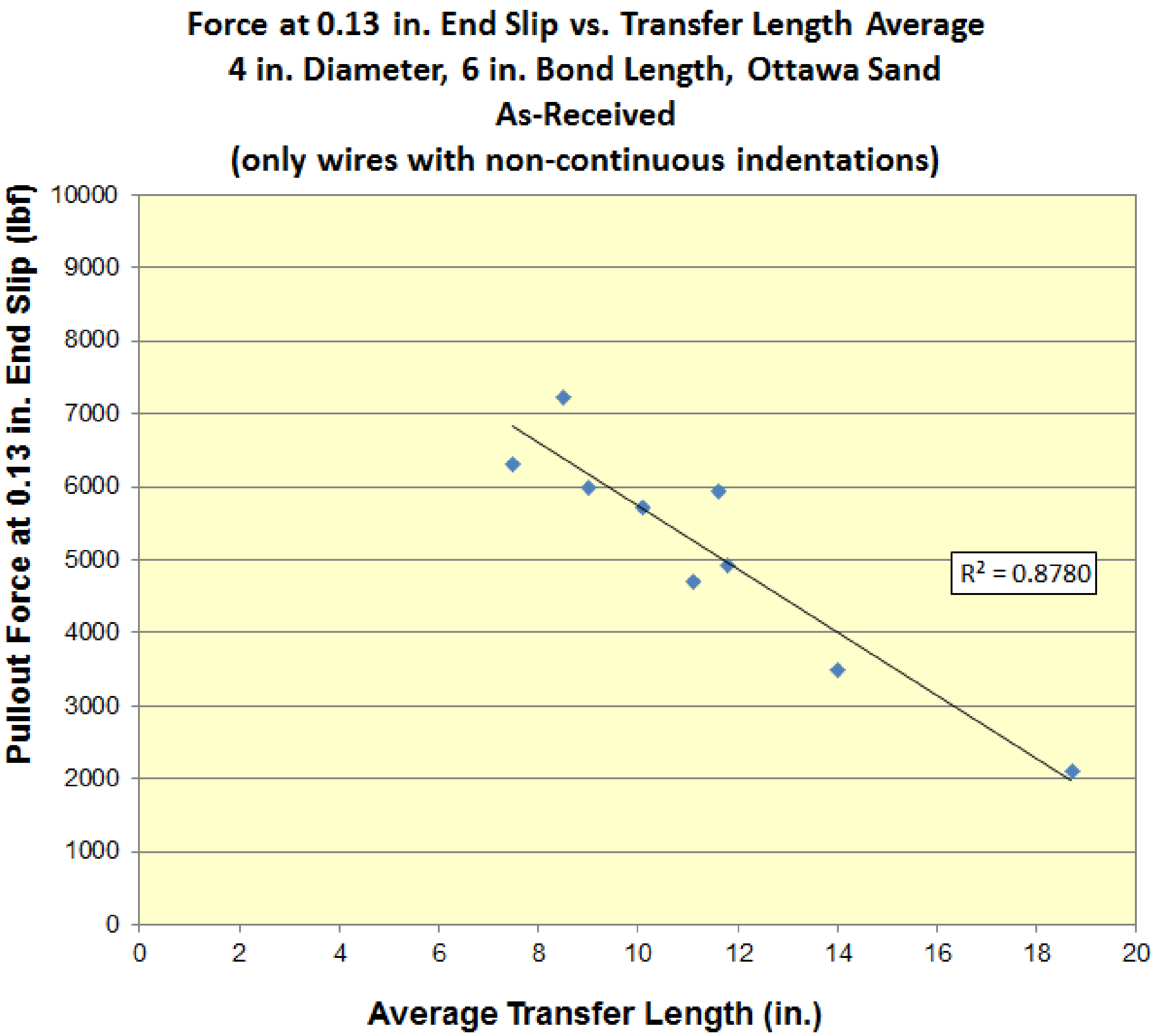


Figure F.26 As-received wires, pullout force at 0.13 in. end slip (individual-indents only)

Table F.14 As-received wires, maximum pullout force

As-Received Pullout Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand Maximum Pullout Force				
Wire	Avg. Pullout Force (lbf)	Std. Dev. (lbf)	C.V. (%)	Transfer Length (in.)
[WA]	487	42	8.7	16.3
[WB]	6481	570	8.8	11.6
[WC]	7646	967	12.6	8.8
[WD]	5555	357	6.4	11.1
[WE]	7674	526	6.9	7.4
[WF]	8312	459	5.5	8.5
[WG]	5505	385	7.0	11.8
[WH]	7605	497	6.5	7.5
[WI]	6567	522	8.0	10.1
[WJ]	7034	635	9.0	9.0
[WK]	3447	354	10.3	14.0
[WL]	2068	322	15.6	18.7

Note: Sample Size = 6

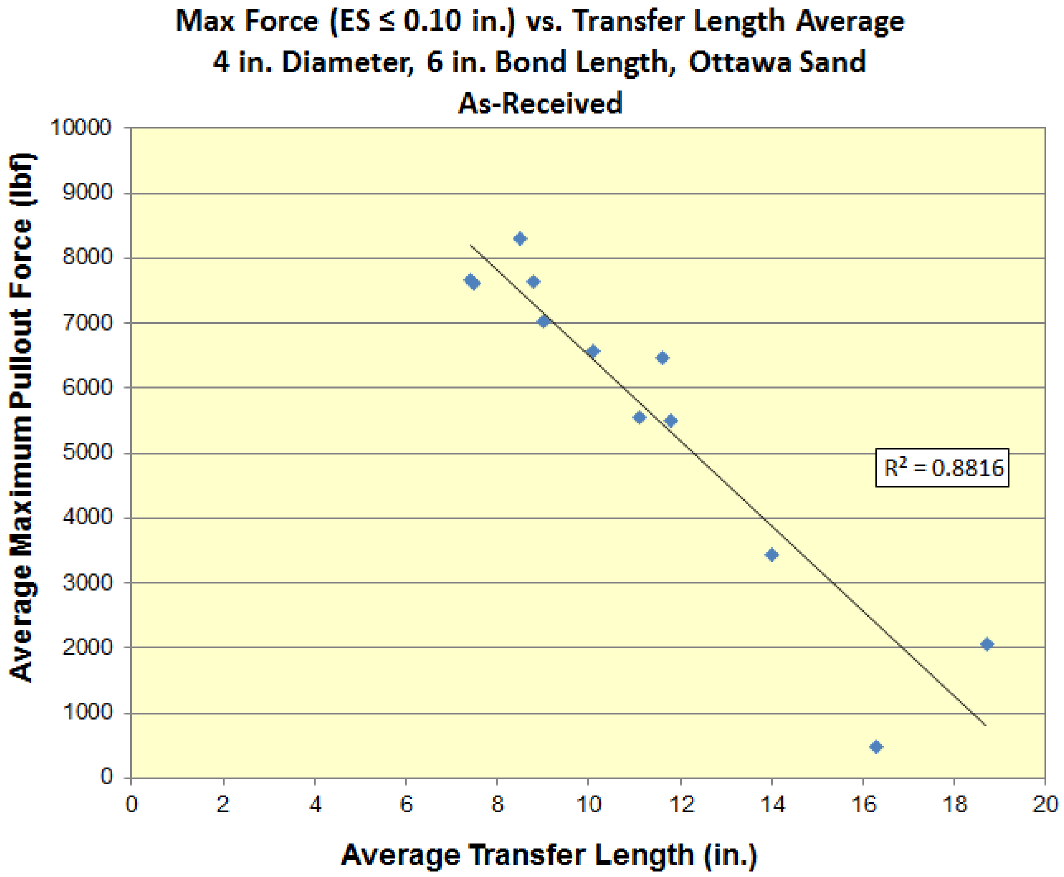


Figure F.27 As-received wires, maximum pullout force

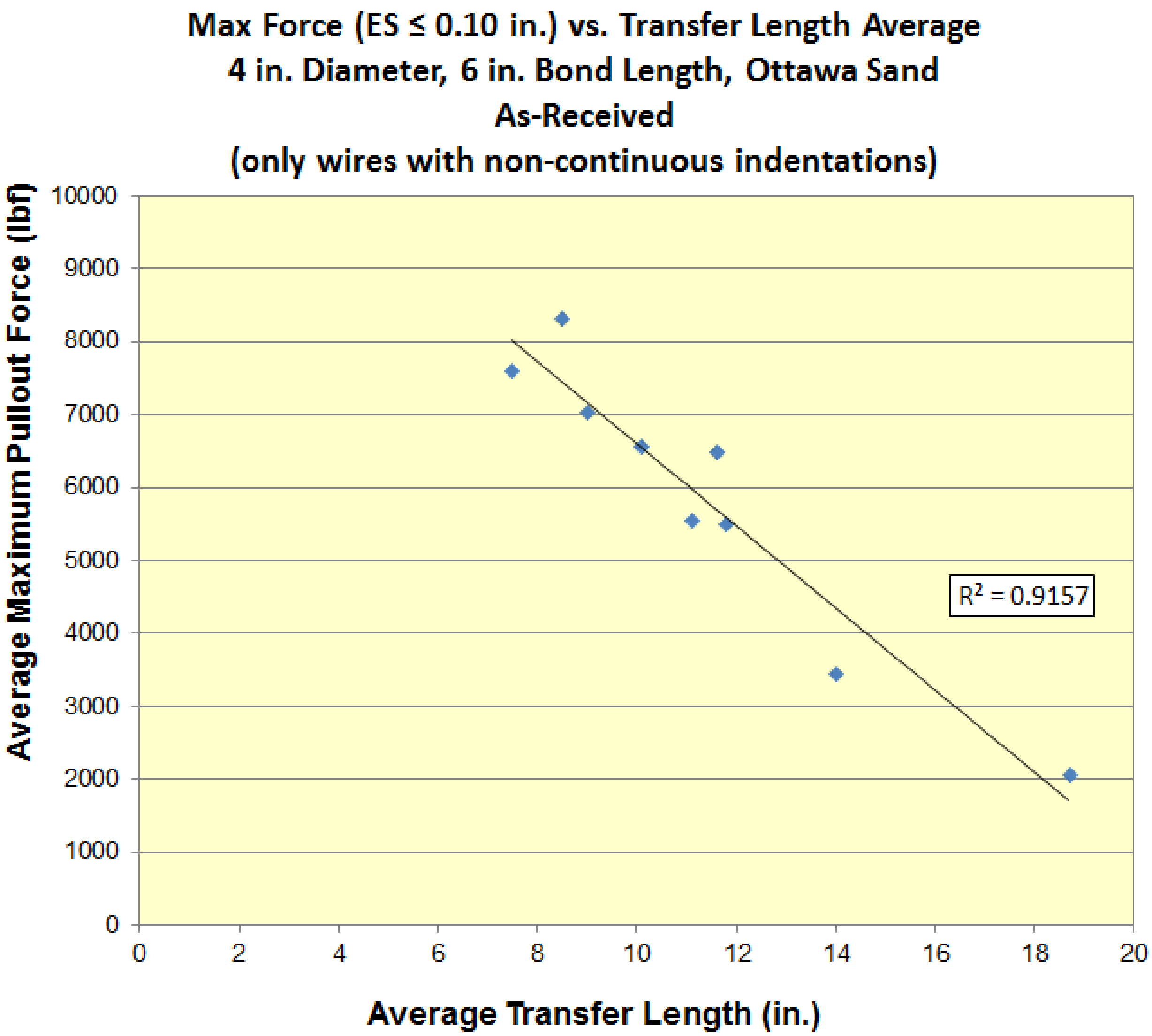
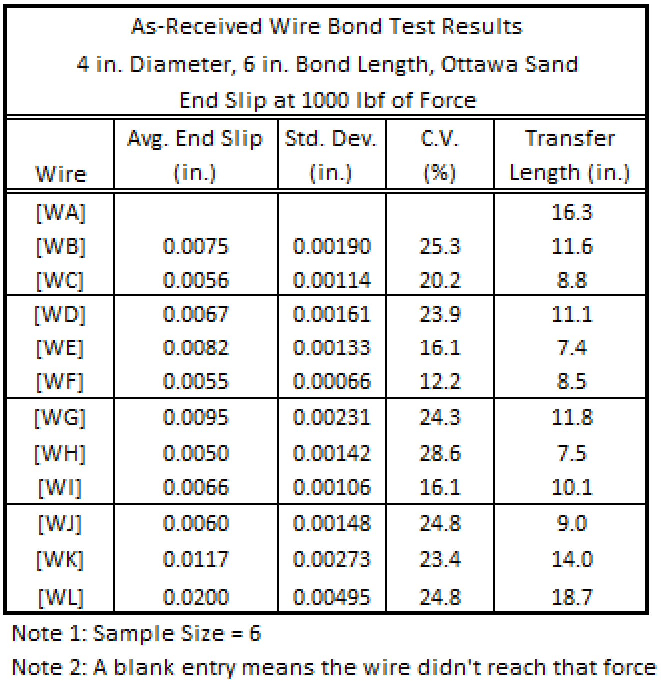


Figure F.28 As-received wires, maximum pullout force (individual-indents only)

Appendix G - Lab Phase, Wire; As-Received End Slips at Certain Force Analysis

Table G.1 As-received wires, end slip at 1000 lbf force



As-Received Wire Bond Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
End Slip at 1000 lbf of Force

Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0075	0.00190	25.3	11.6
[WC]	0.0056	0.00114	20.2	8.8
[WD]	0.0067	0.00161	23.9	11.1
[WE]	0.0082	0.00133	16.1	7.4
[WF]	0.0055	0.00066	12.2	8.5
[WG]	0.0095	0.00231	24.3	11.8
[WH]	0.0050	0.00142	28.6	7.5
[WI]	0.0066	0.00106	16.1	10.1
[WJ]	0.0060	0.00148	24.8	9.0
[WK]	0.0117	0.00273	23.4	14.0
[WL]	0.0200	0.00495	24.8	18.7

Note 1: Sample Size = 6
Note 2: A blank entry means the wire didn't reach that force

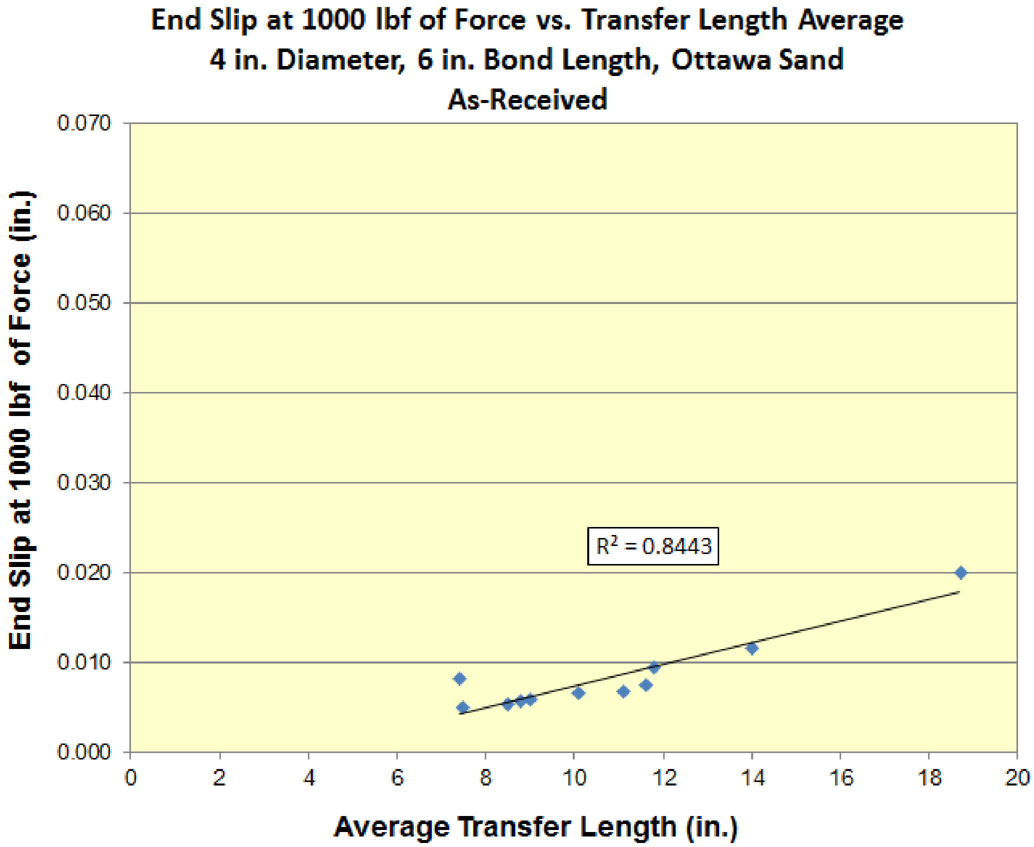


Figure G.1 As-received wires, end slip at 1000 lbf force

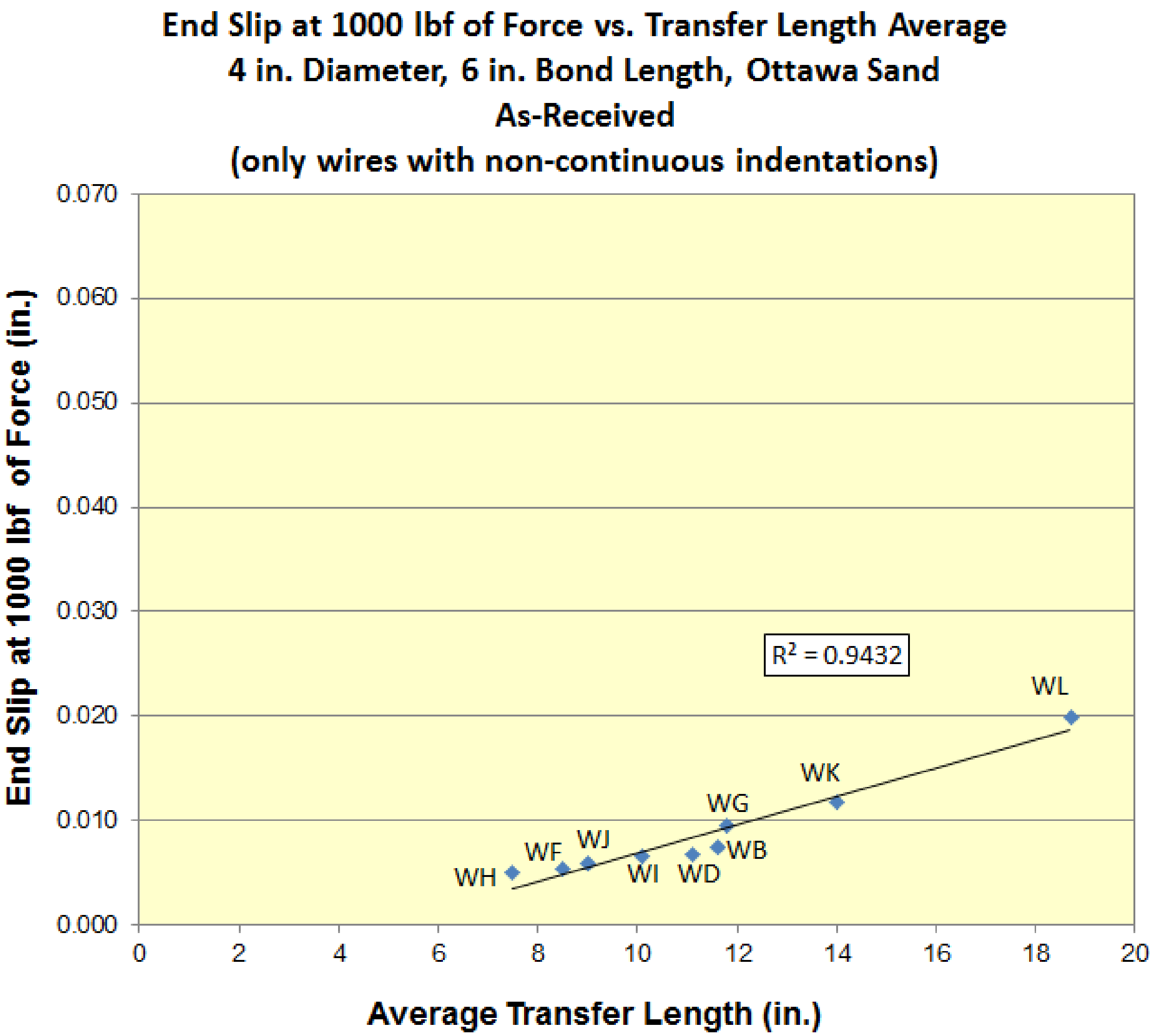


Figure G.2 As-received wires, end slip at 1000 lbf force (individual-indents only)

Table G.2 As-received wires, end slip at 1500 lbf force

As-Received Wire Bond Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
End Slip at 1500 lbf of Force

Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0101	0.00208	20.6	11.6
[WC]	0.0093	0.00150	16.2	8.8
[WD]	0.0092	0.00173	18.9	11.1
[WE]	0.0118	0.00145	12.3	7.4
[WF]	0.0074	0.00074	10.0	8.5
[WG]	0.0136	0.00284	20.9	11.8
[WH]	0.0068	0.00121	17.7	7.5
[WI]	0.0093	0.00108	11.7	10.1
[WJ]	0.0081	0.00186	23.0	9.0
[WK]	0.0180	0.00342	19.1	14.0
[WL]	0.0400	0.01658	41.5	18.7

Note 1: Sample Size = 6

Note 2: A blank entry means the wire didn't reach that force

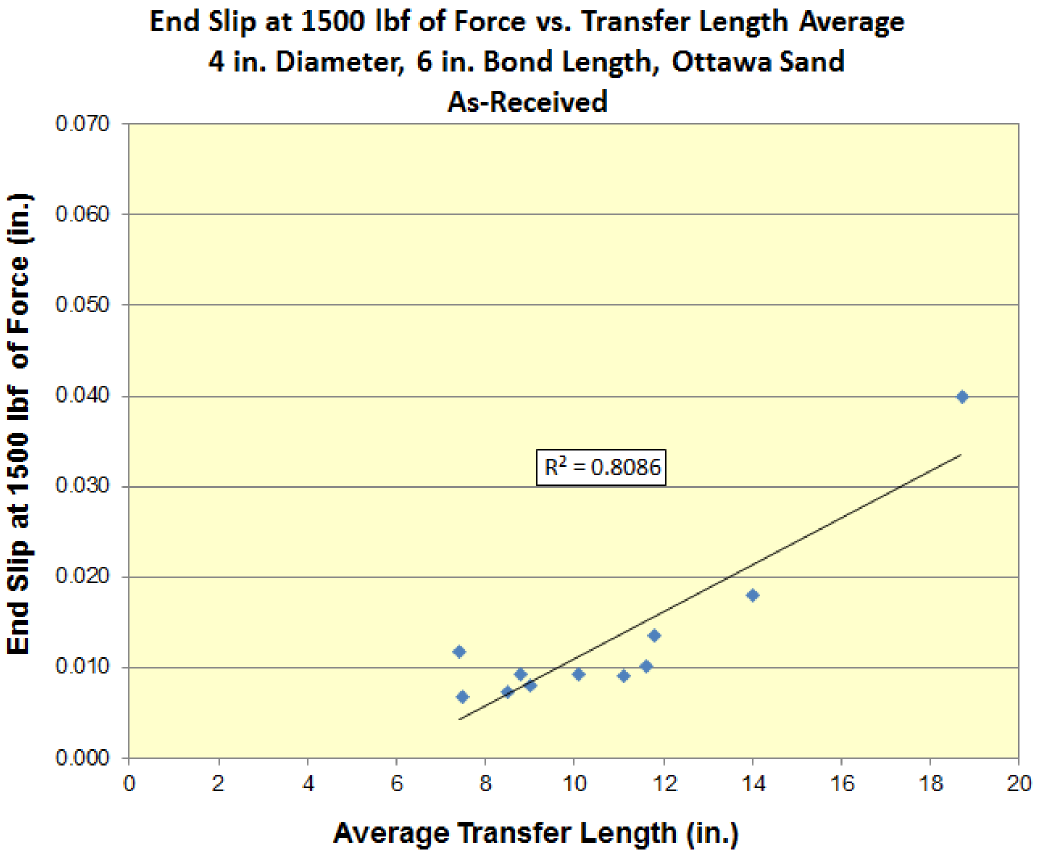


Figure G.3 As-received wires, end slip at 1500 lbf force

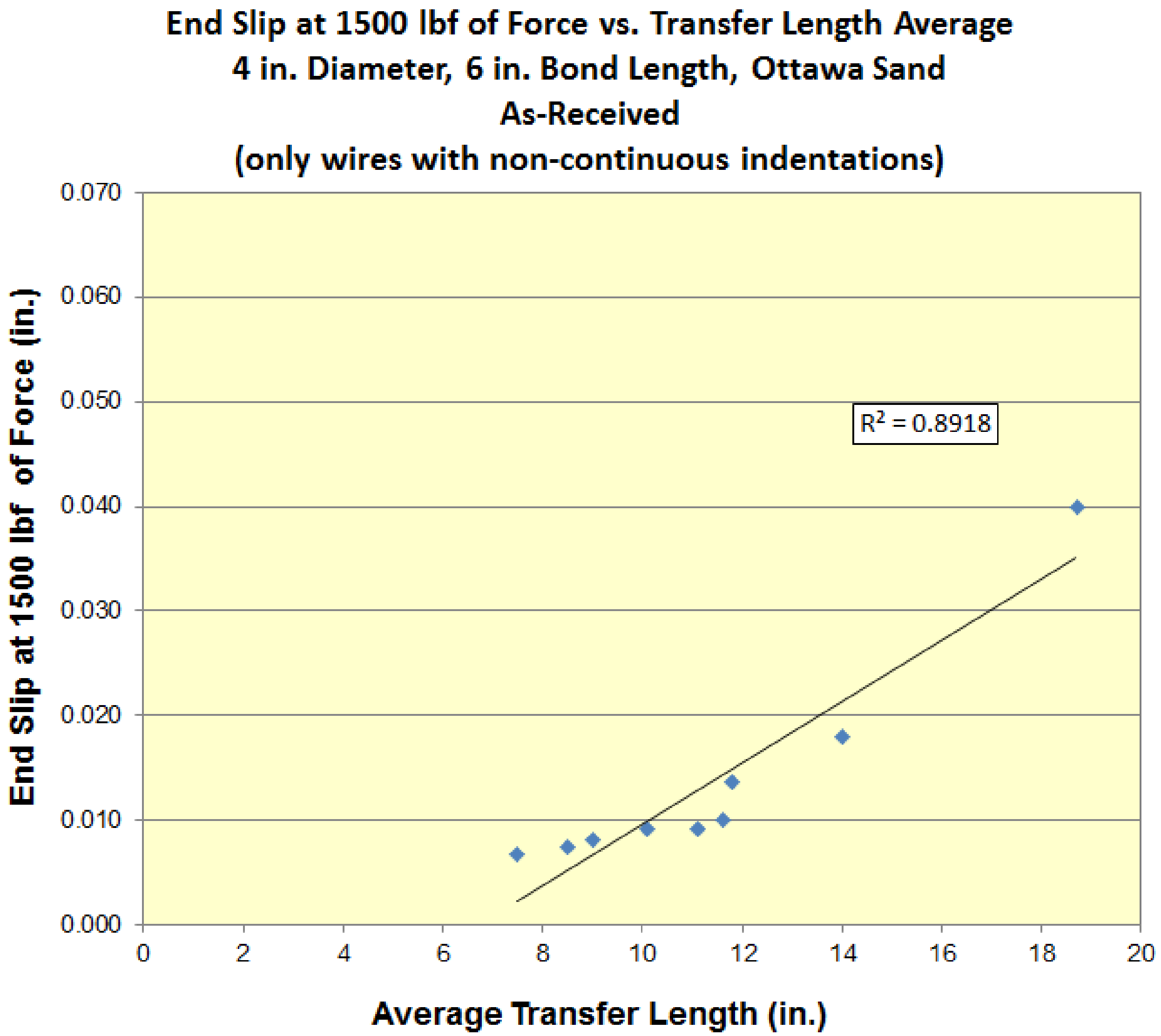


Figure G.4 As-received wires, end slip at 1500 lbf force (individual-indents only)

Table G.3 As-received wires, end slip at 2000 lbf force

As-Received Wire Bond Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
End Slip at 2000 lbf of Force

Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0124	0.00235	19.0	11.6
[WC]	0.0130	0.00210	16.1	8.8
[WD]	0.0113	0.00190	16.9	11.1
[WE]	0.0152	0.00202	13.3	7.4
[WF]	0.0091	0.00081	9.0	8.5
[WG]	0.0175	0.00322	18.4	11.8
[WH]	0.0086	0.00106	12.4	7.5
[WI]	0.0119	0.00116	9.8	10.1
[WJ]	0.0100	0.00200	20.0	9.0
[WK]	0.0264	0.00510	19.3	14.0
[WL]	0.0647	0.02199	34.0	18.7

Note 1: Sample Size = 6, L = 4
Note 2: A blank entry means the wire didn't reach that force

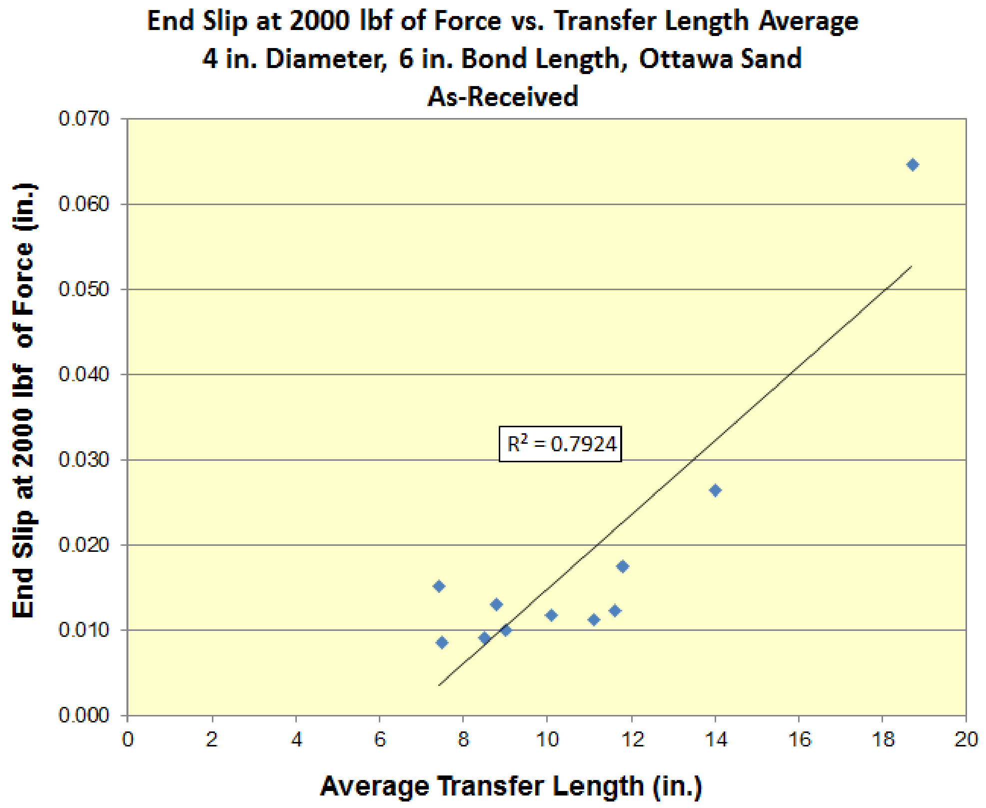


Figure G.5 As-received wires, end slip at 2000 lbf force

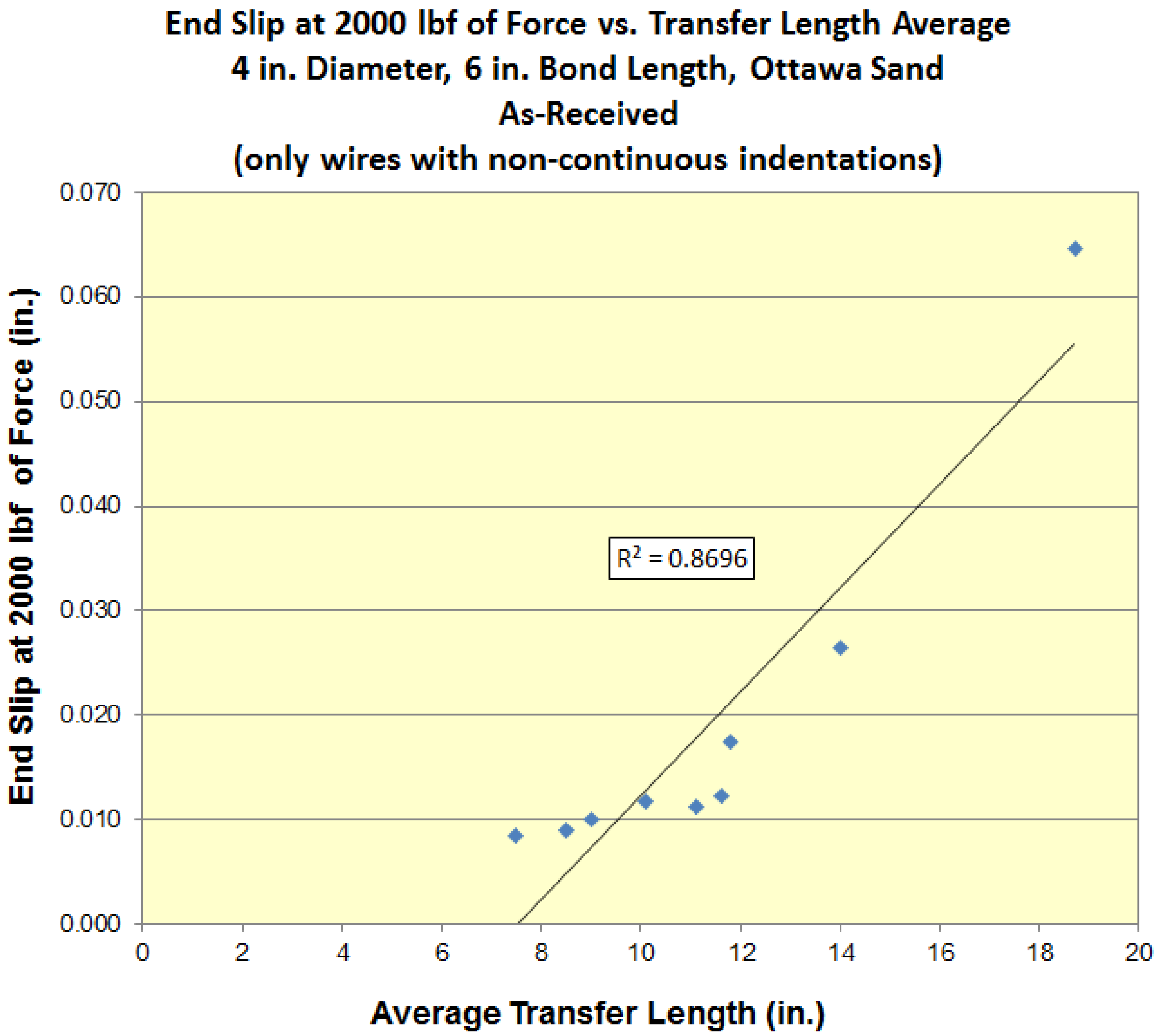
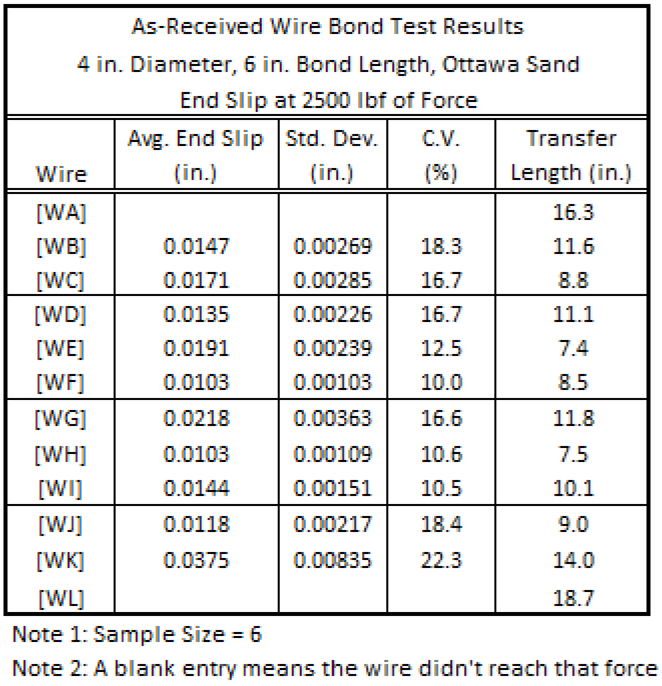


Figure G.6 As-received wires, end slip at 2000 lbf force (individual-indents only)

Table G.4 As-received wires, end slip at 2500 lbf force



As-Received Wire Bond Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
End Slip at 2500 lbf of Force

Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0147	0.00269	18.3	11.6
[WC]	0.0171	0.00285	16.7	8.8
[WD]	0.0135	0.00226	16.7	11.1
[WE]	0.0191	0.00239	12.5	7.4
[WF]	0.0103	0.00103	10.0	8.5
[WG]	0.0218	0.00363	16.6	11.8
[WH]	0.0103	0.00109	10.6	7.5
[WI]	0.0144	0.00151	10.5	10.1
[WJ]	0.0118	0.00217	18.4	9.0
[WK]	0.0375	0.00835	22.3	14.0
[WL]				18.7

Note 1: Sample Size = 6
Note 2: A blank entry means the wire didn't reach that force

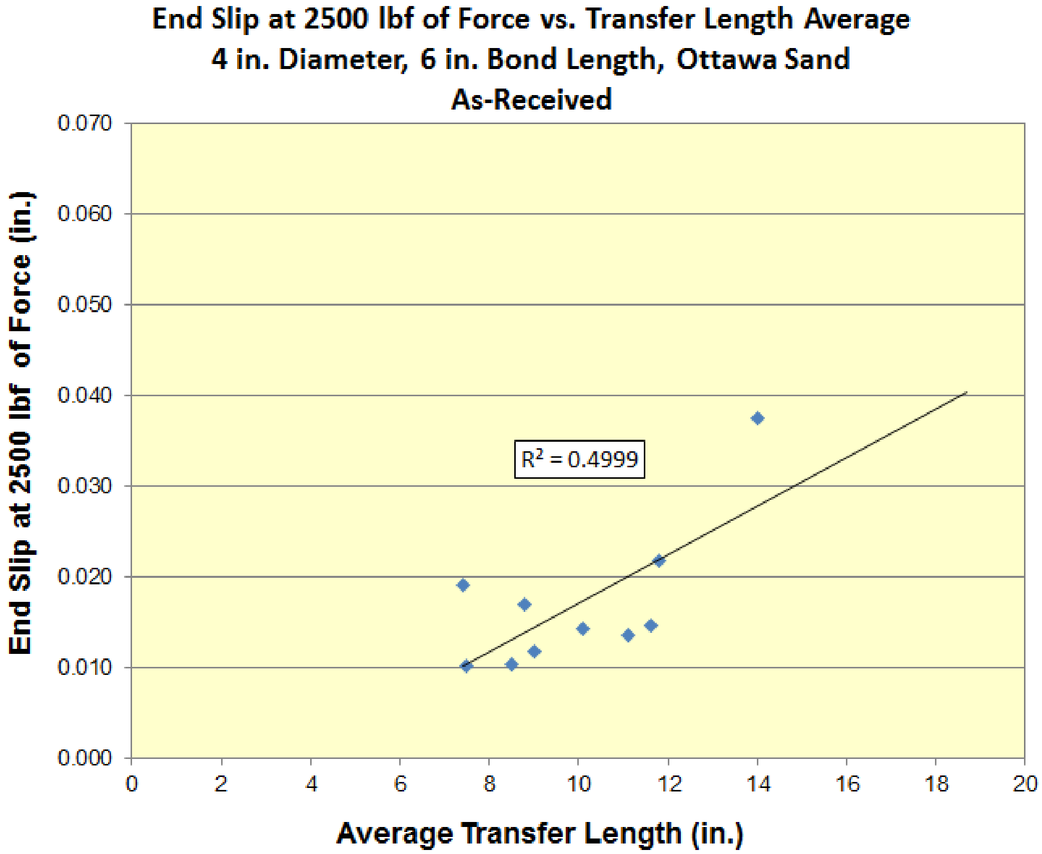


Figure G.7 As-received wires, end slip at 2500 lbf force

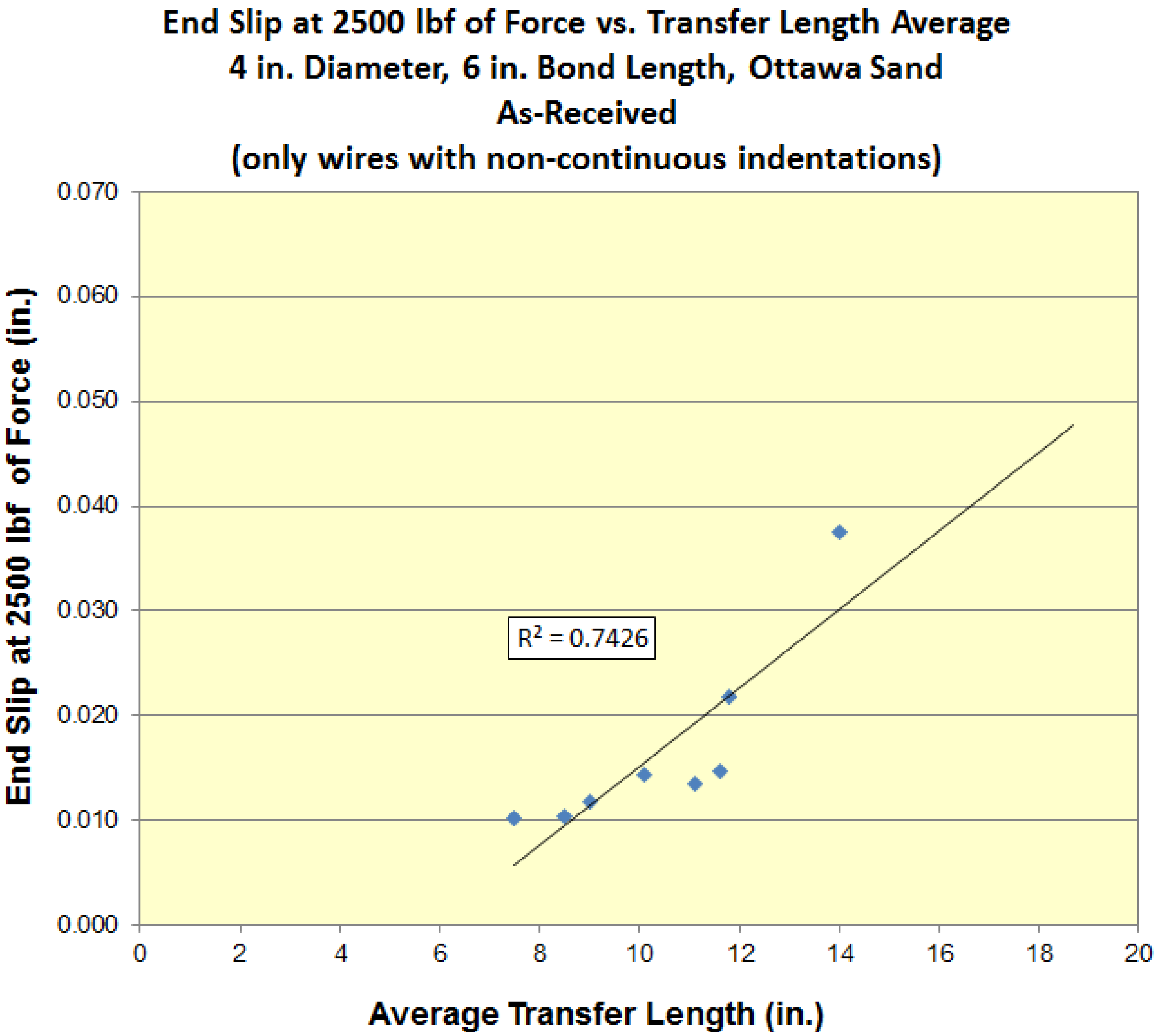


Figure G.8 As-received wires, end slip at 2500 lbf force (individual-indents only)

Table G.5 As-received wires, end slip at 3000 lbf force

As-Received Wire Bond Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
End Slip at 3000 lbf of Force

Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0175	0.00310	17.7	11.6
[WC]	0.0219	0.00356	16.3	8.8
[WD]	0.0159	0.00248	15.6	11.1
[WE]	0.0231	0.00272	11.8	7.4
[WF]	0.0120	0.00117	9.7	8.5
[WG]	0.0265	0.00415	15.7	11.8
[WH]	0.0119	0.00108	9.1	7.5
[WI]	0.0168	0.00197	11.7	10.1
[WJ]	0.0137	0.00246	17.9	9.0
[WK]	0.0583	0.02030	34.8	14.0
[WL]				18.7

Note 1: Sample Size = 6

Note 2: A blank entry means the wire didn't reach that force

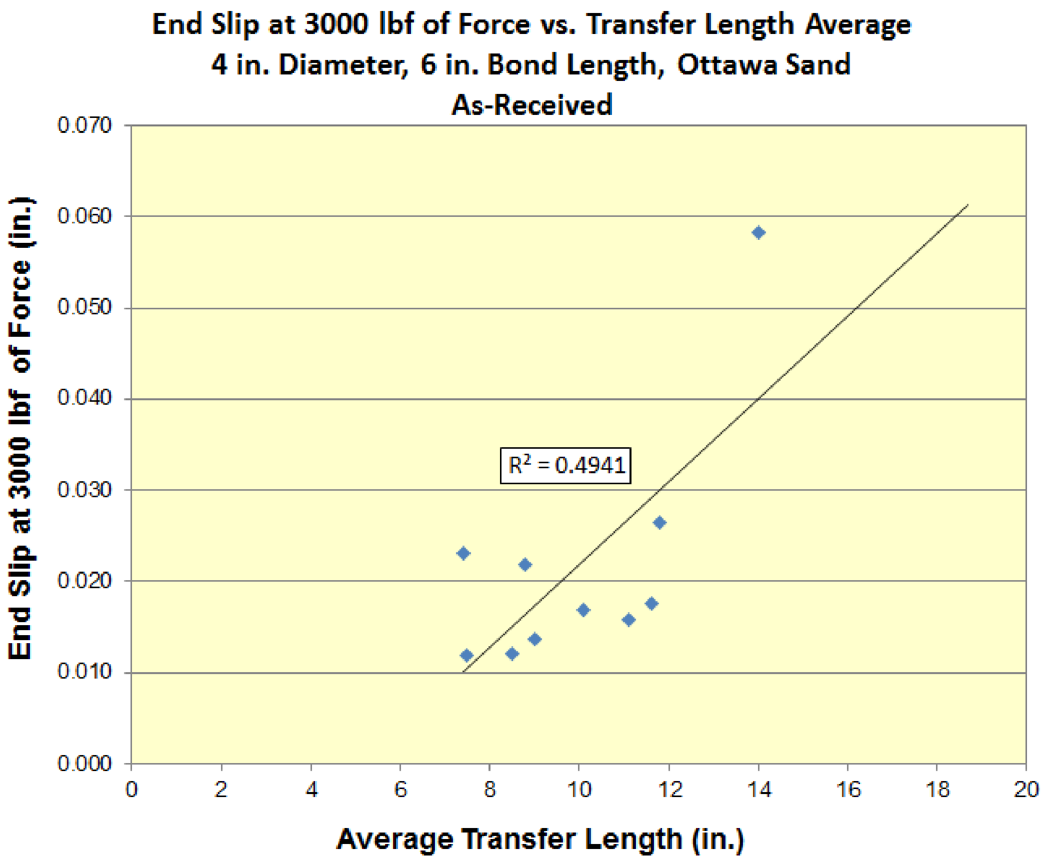


Figure G.9 As-received wires, end slip at 3000 lbf force

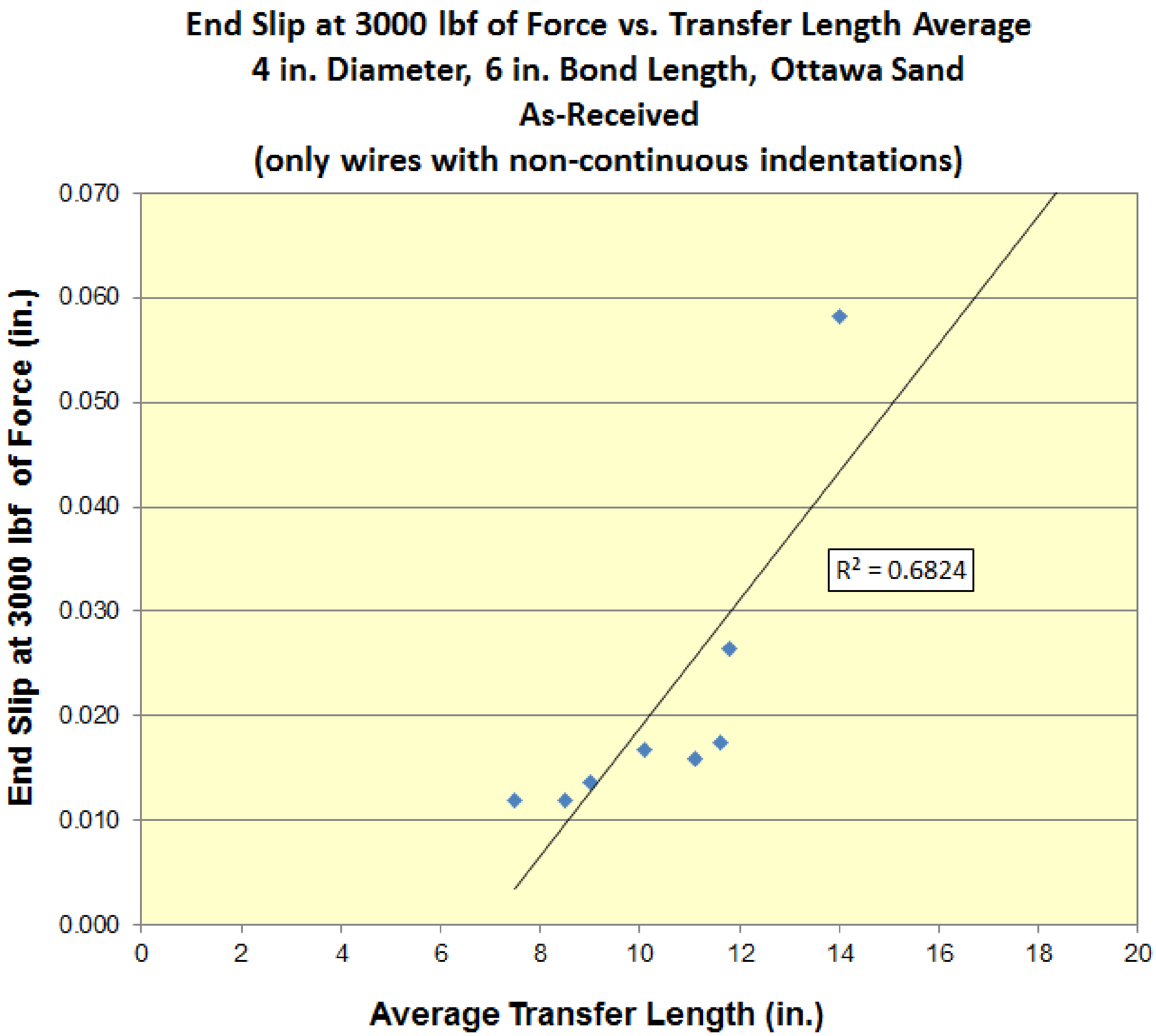


Figure G.10 As-received wires, end slip at 3000 lbf force (individual-indents only)

Table G.6 As-received wires, end slip at 3500 lbf force

As-Received Wire Bond Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
End Slip at 3500 lbf of Force

Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0207	0.00372	17.9	11.6
[WC]	0.0273	0.00459	16.8	8.8
[WD]	0.0189	0.00294	15.5	11.1
[WE]	0.0276	0.00315	11.4	7.4
[WF]	0.0134	0.00135	10.0	8.5
[WG]	0.0322	0.00525	16.3	11.8
[WH]	0.0136	0.00140	10.2	7.5
[WI]	0.0196	0.00238	12.1	10.1
[WJ]	0.0158	0.00296	18.7	9.0
[WK]	0.0611	0.00449	7.3	14.0
[WL]				18.7

Note 1: Sample Size = 6, K = 2
Note 2: A blank entry means the wire didn't reach that force

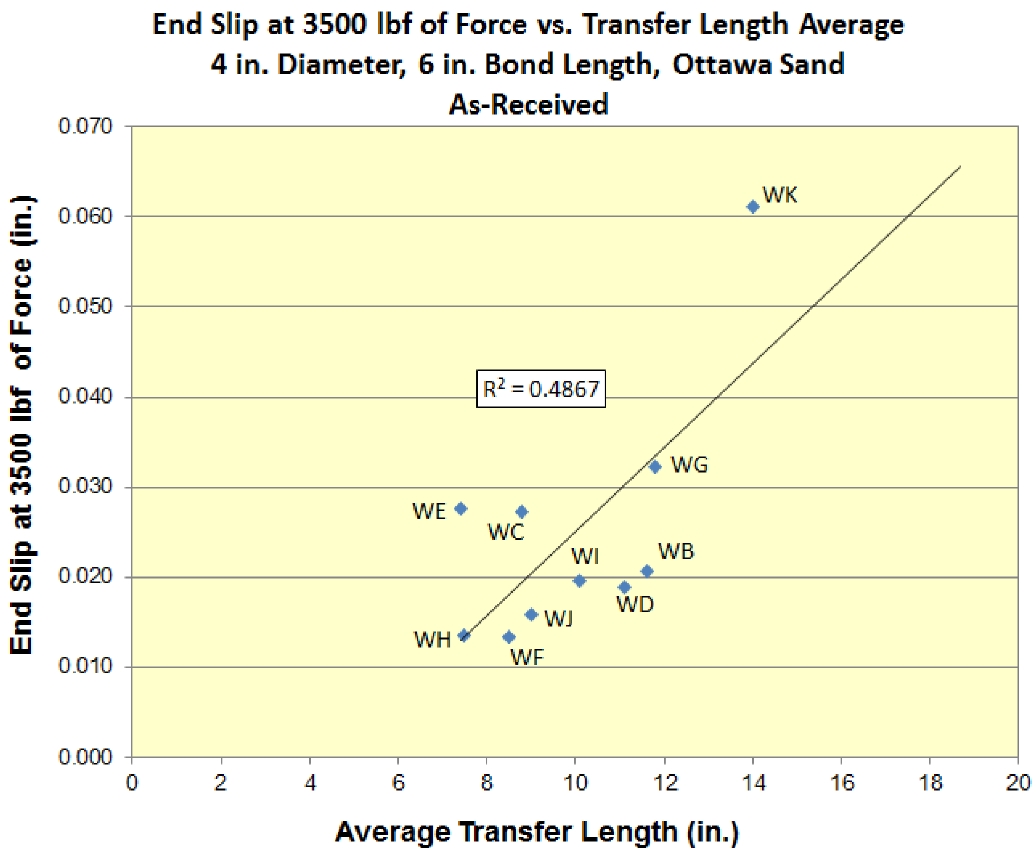


Figure G.11 As-received wires, end slip at 3500 lbf force

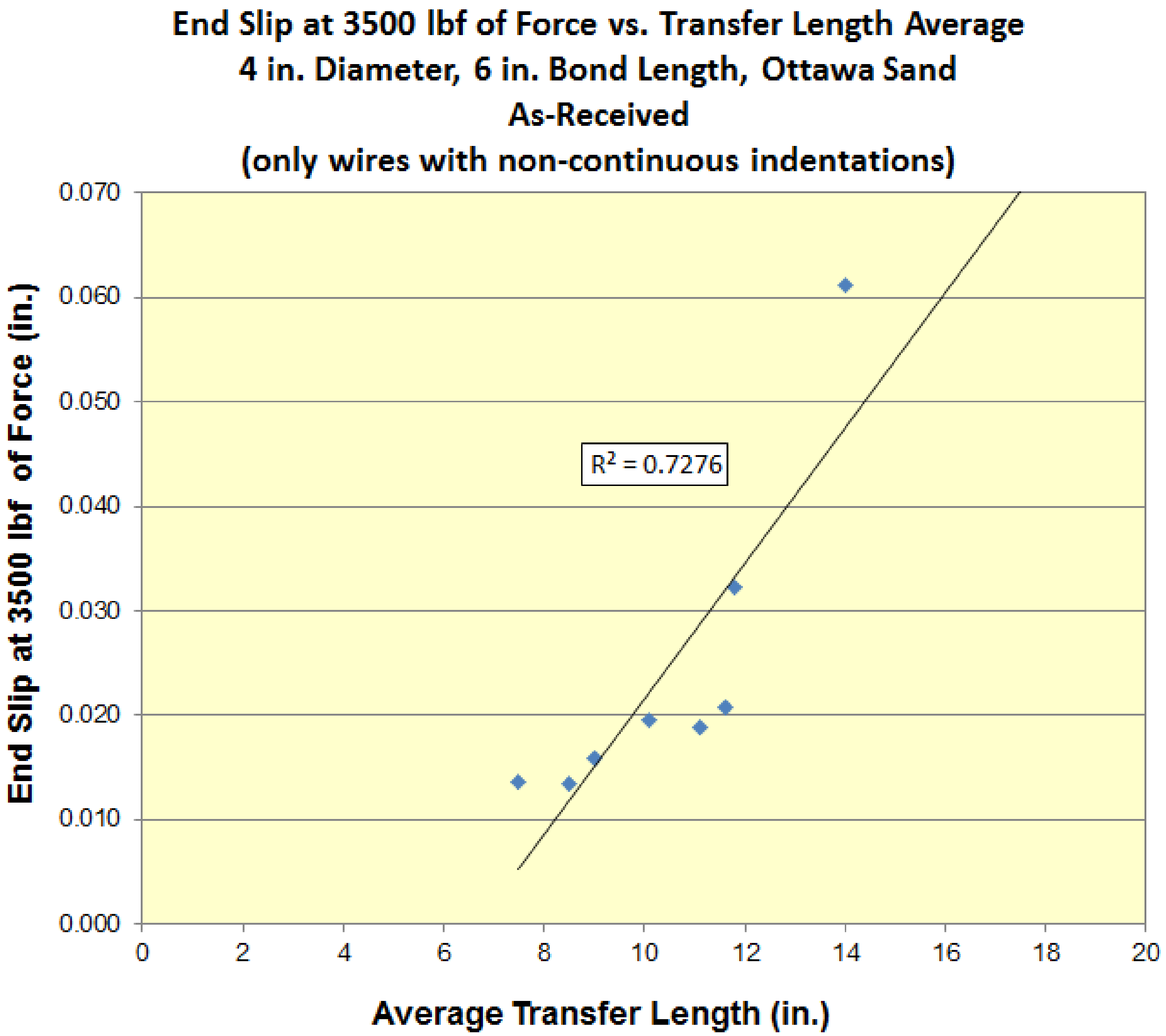
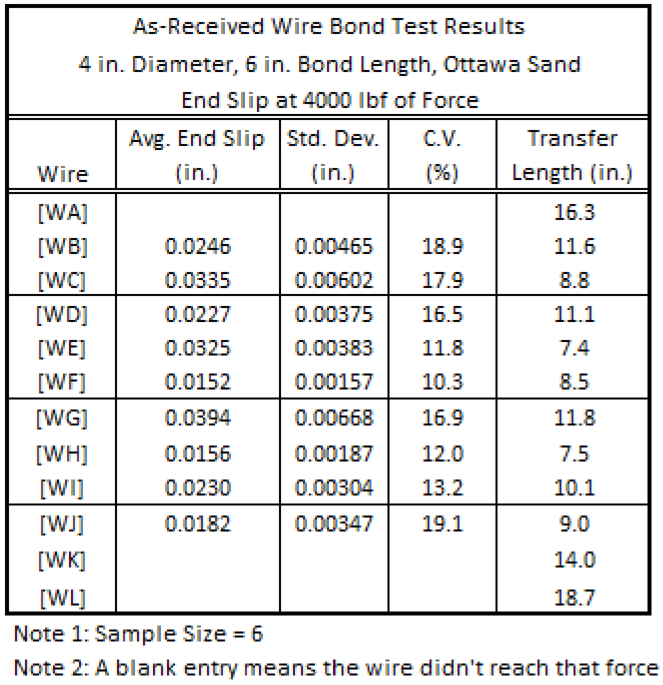


Figure G.12 As-received wires, end slip at 3500 lbf force (individual-indents only)

Table G.7 As-received wires, end slip at 4000 lbf force



As-Received Wire Bond Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
End Slip at 4000 lbf of Force

Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0246	0.00465	18.9	11.6
[WC]	0.0335	0.00602	17.9	8.8
[WD]	0.0227	0.00375	16.5	11.1
[WE]	0.0325	0.00383	11.8	7.4
[WF]	0.0152	0.00157	10.3	8.5
[WG]	0.0394	0.00668	16.9	11.8
[WH]	0.0156	0.00187	12.0	7.5
[WI]	0.0230	0.00304	13.2	10.1
[WJ]	0.0182	0.00347	19.1	9.0
[WK]				14.0
[WL]				18.7

Note 1: Sample Size = 6
Note 2: A blank entry means the wire didn't reach that force

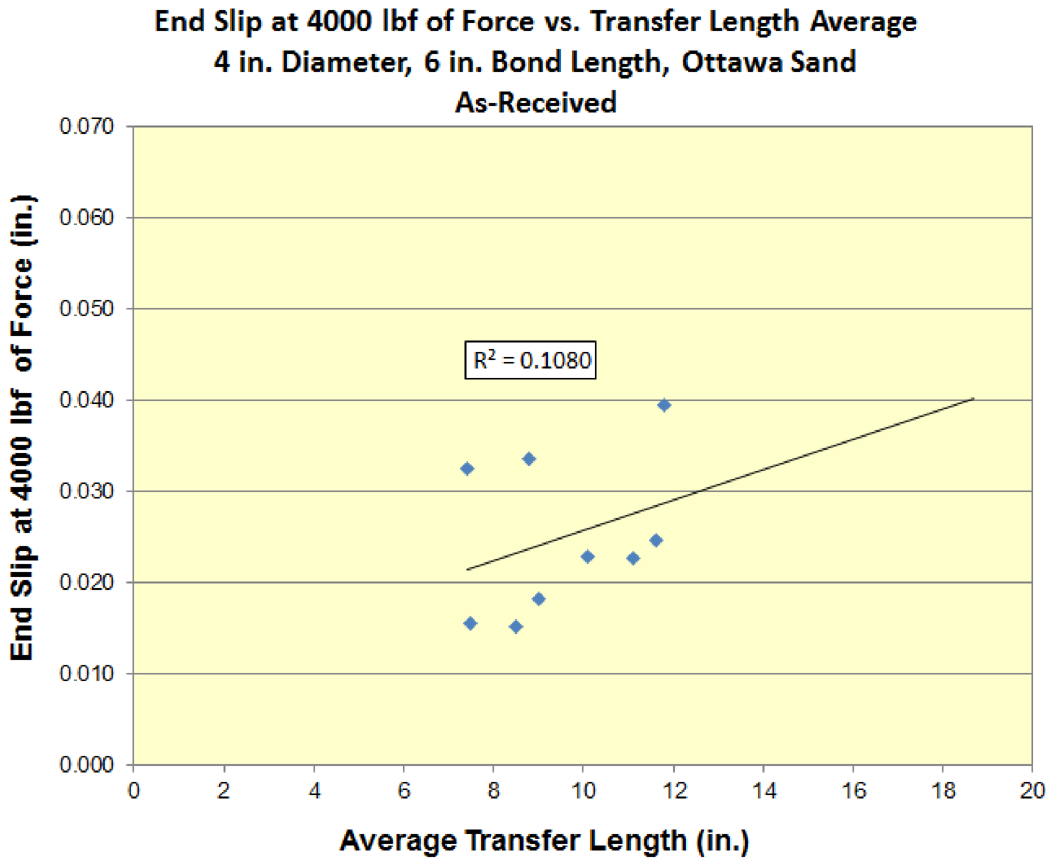


Figure G.13 As-received wires, end slip at 4000 lbf force

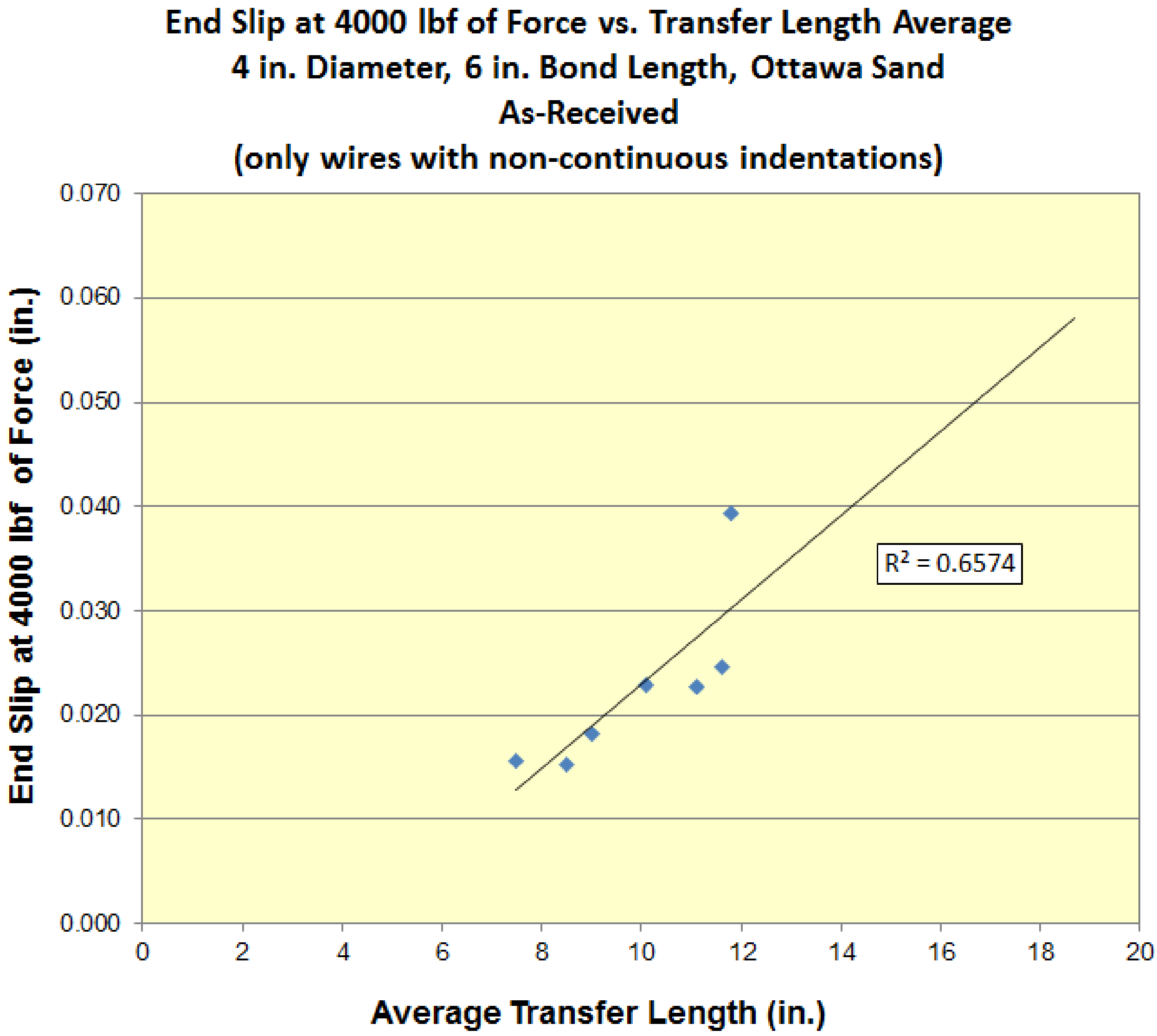


Figure G.14 As-received wires, end slip at 4000 lbf force (individual-indents only)

Table G.8 As-received wires, end slip at 4500 lbf force

As-Received Wire Bond Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
End Slip at 4500 lbf of Force

Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0302	0.00664	22.0	11.6
[WC]	0.0406	0.00764	18.8	8.8
[WD]	0.0280	0.00523	18.7	11.1
[WE]	0.0382	0.00443	11.6	7.4
[WF]	0.0171	0.00192	11.2	8.5
[WG]	0.0488	0.00875	17.9	11.8
[WH]	0.0180	0.00224	12.5	7.5
[WI]	0.0271	0.00397	14.7	10.1
[WJ]	0.0213	0.00434	20.4	9.0
[WK]				14.0
[WL]				18.7

Note 1: Sample Size = 6
Note 2: A blank entry means the wire didn't reach that force

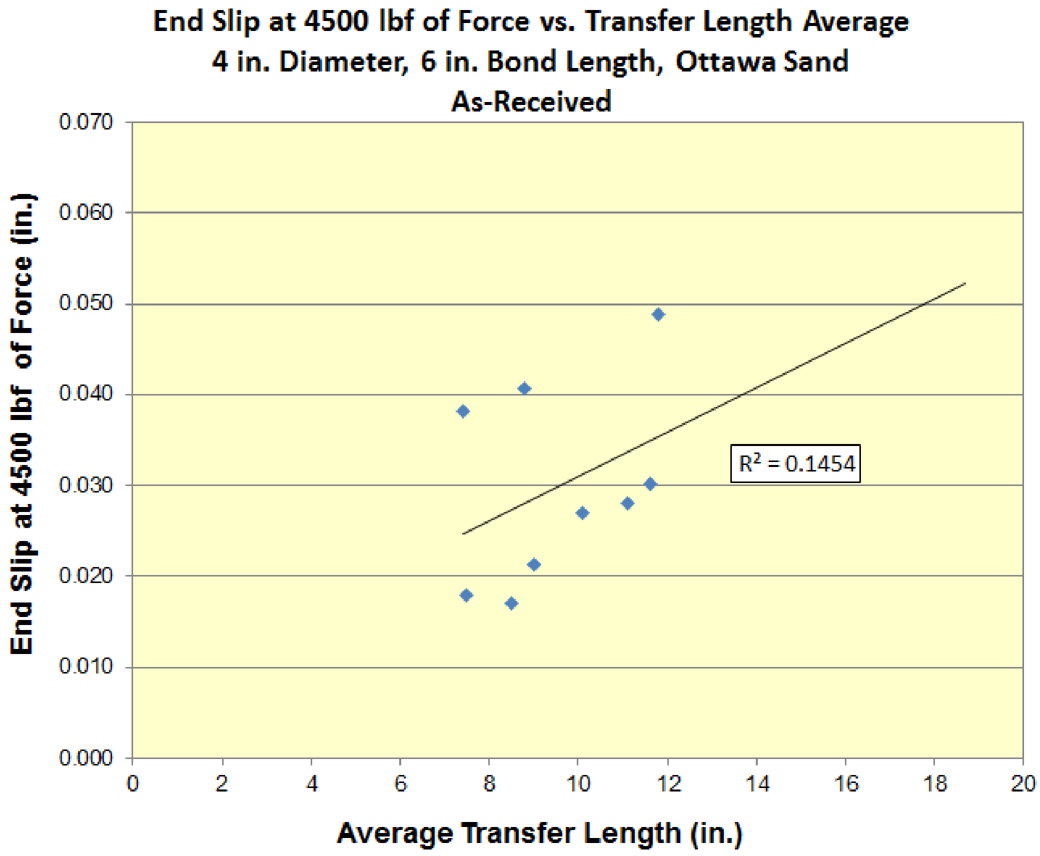


Figure G.15 As-received wires, end slip at 4500 lbf force

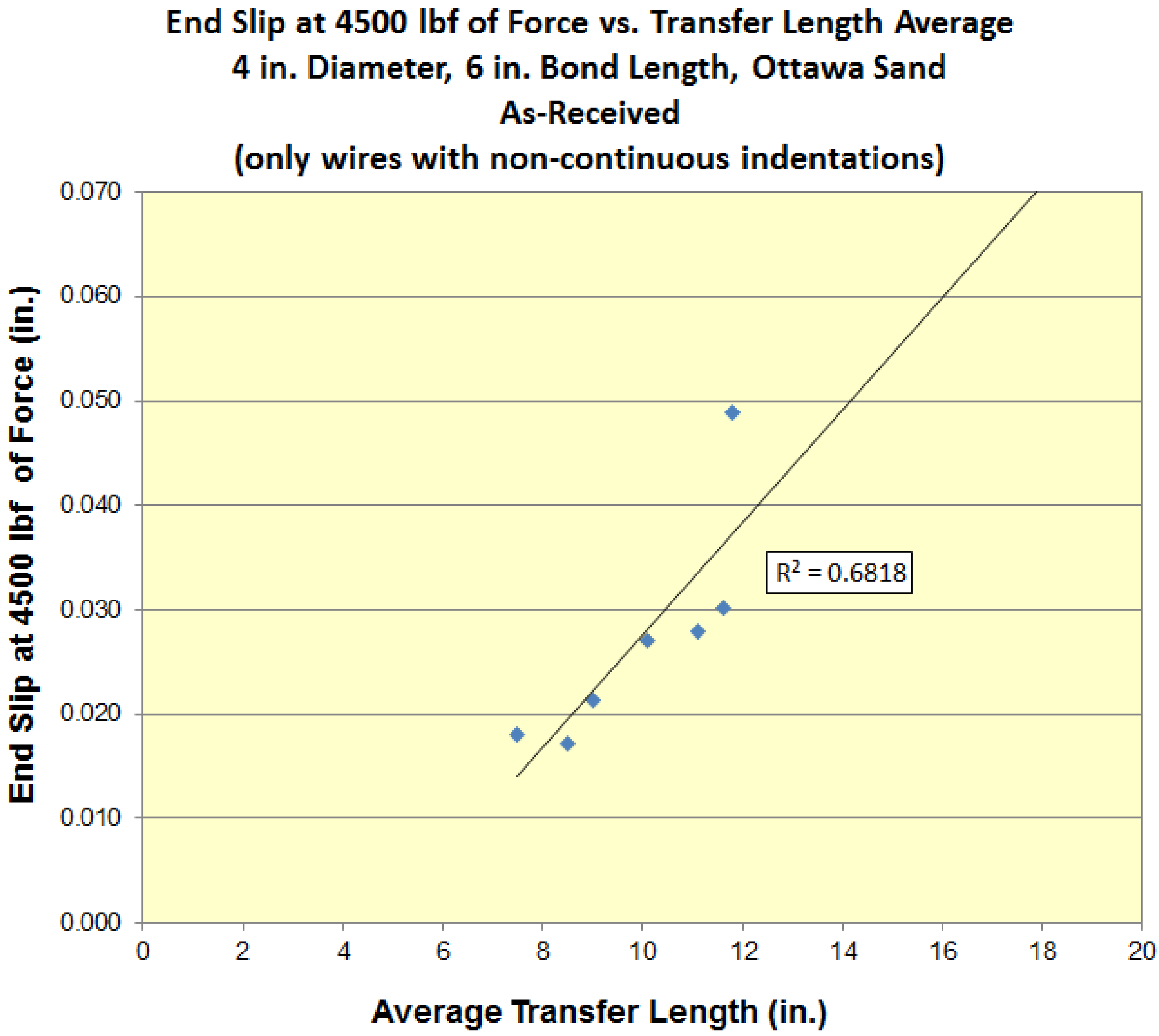
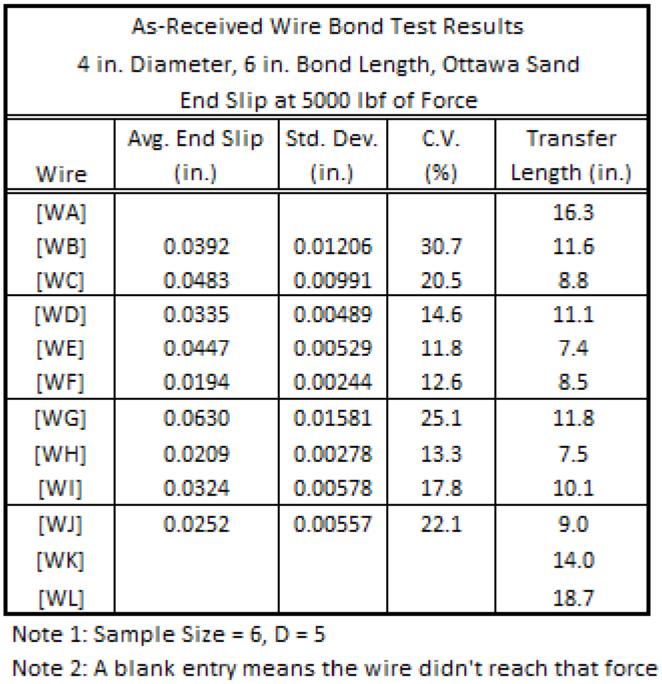


Figure G.16 As-received wires, end slip at 4500 lbf force (individual-indents only)

Table G.9 As-received wires, end slip at 5000 lbf force



As-Received Wire Bond Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
End Slip at 5000 lbf of Force

Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0392	0.01206	30.7	11.6
[WC]	0.0483	0.00991	20.5	8.8
[WD]	0.0335	0.00489	14.6	11.1
[WE]	0.0447	0.00529	11.8	7.4
[WF]	0.0194	0.00244	12.6	8.5
[WG]	0.0630	0.01581	25.1	11.8
[WH]	0.0209	0.00278	13.3	7.5
[WI]	0.0324	0.00578	17.8	10.1
[WJ]	0.0252	0.00557	22.1	9.0
[WK]				14.0
[WL]				18.7

Note 1: Sample Size = 6, D = 5

Note 2: A blank entry means the wire didn't reach that force

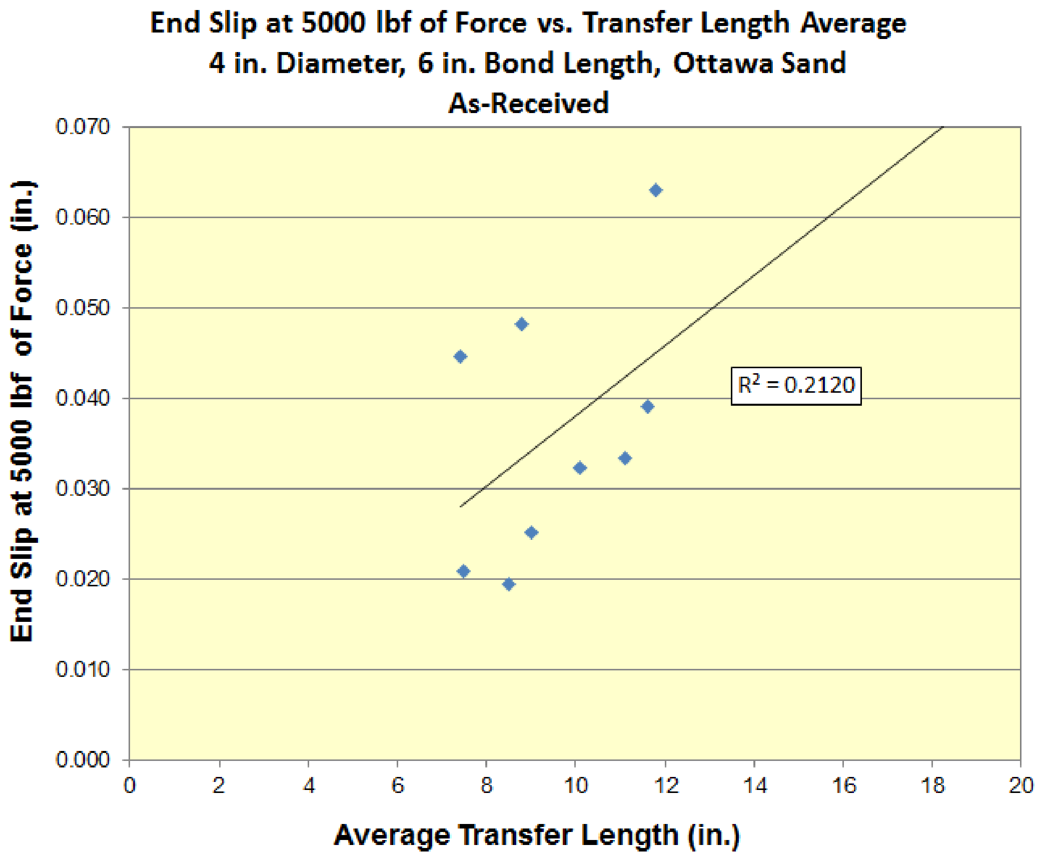


Figure G.17 As-received wires, end slip at 5000 lbf force

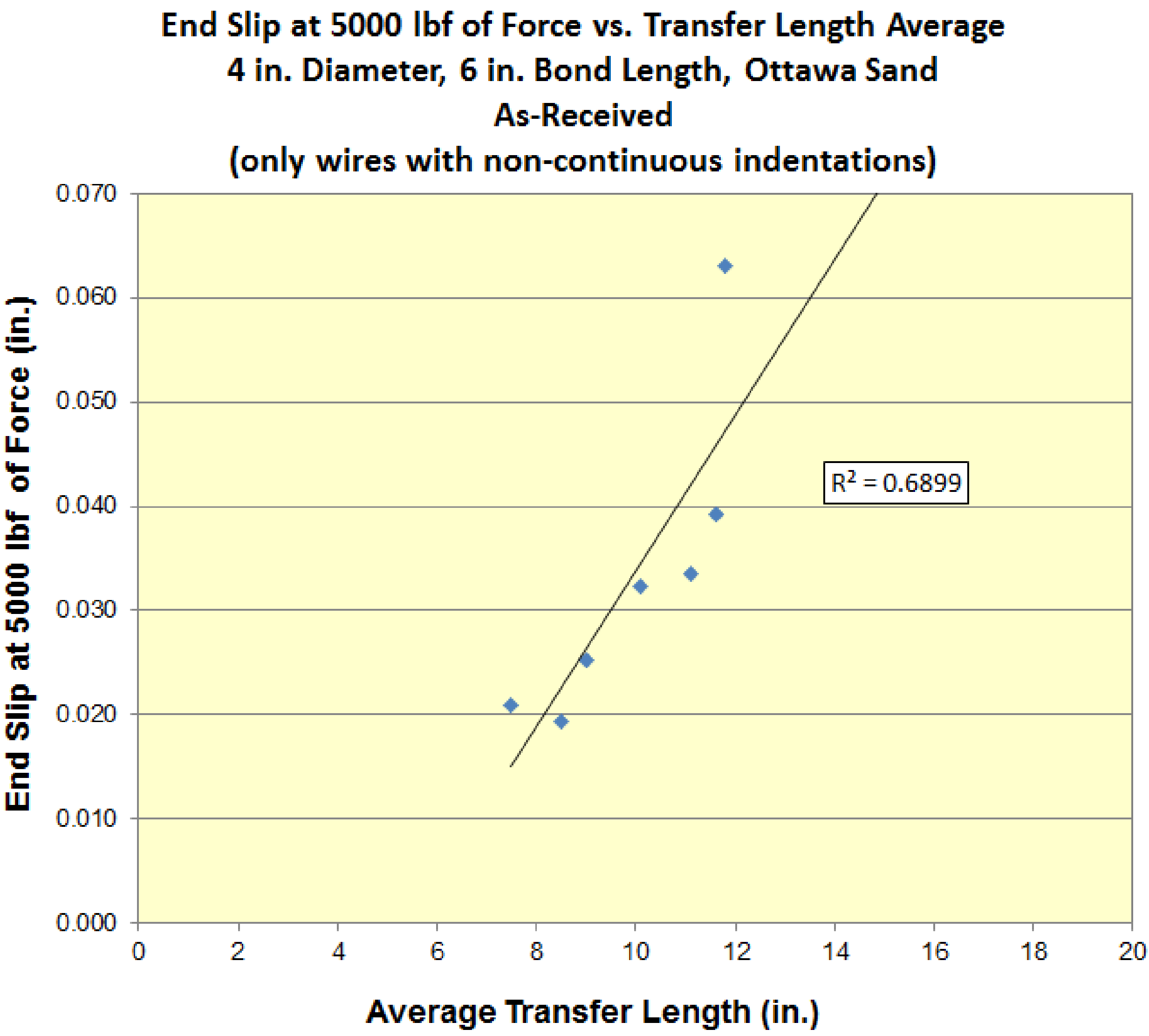
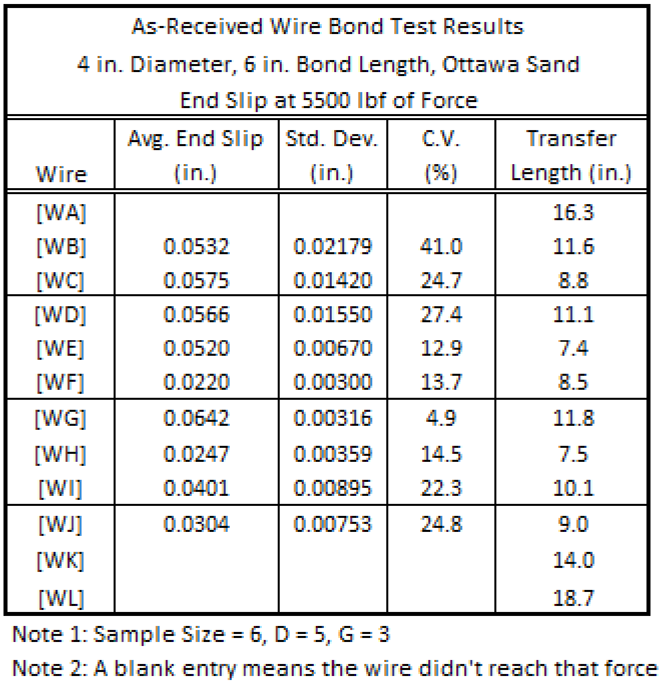


Figure G.18 As-received wires, end slip at 5000 lbf force (individual-indents only)

Table G.10 As-received wires, end slip at 5500 lbf force



As-Received Wire Bond Test Results 4 in. Diameter, 6 in. Bond Length, Ottawa Sand End Slip at 5500 lbf of Force				
Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0532	0.02179	41.0	11.6
[WC]	0.0575	0.01420	24.7	8.8
[WD]	0.0566	0.01550	27.4	11.1
[WE]	0.0520	0.00670	12.9	7.4
[WF]	0.0220	0.00300	13.7	8.5
[WG]	0.0642	0.00316	4.9	11.8
[WH]	0.0247	0.00359	14.5	7.5
[WI]	0.0401	0.00895	22.3	10.1
[WJ]	0.0304	0.00753	24.8	9.0
[WK]				14.0
[WL]				18.7

Note 1: Sample Size = 6, D = 5, G = 3

Note 2: A blank entry means the wire didn't reach that force

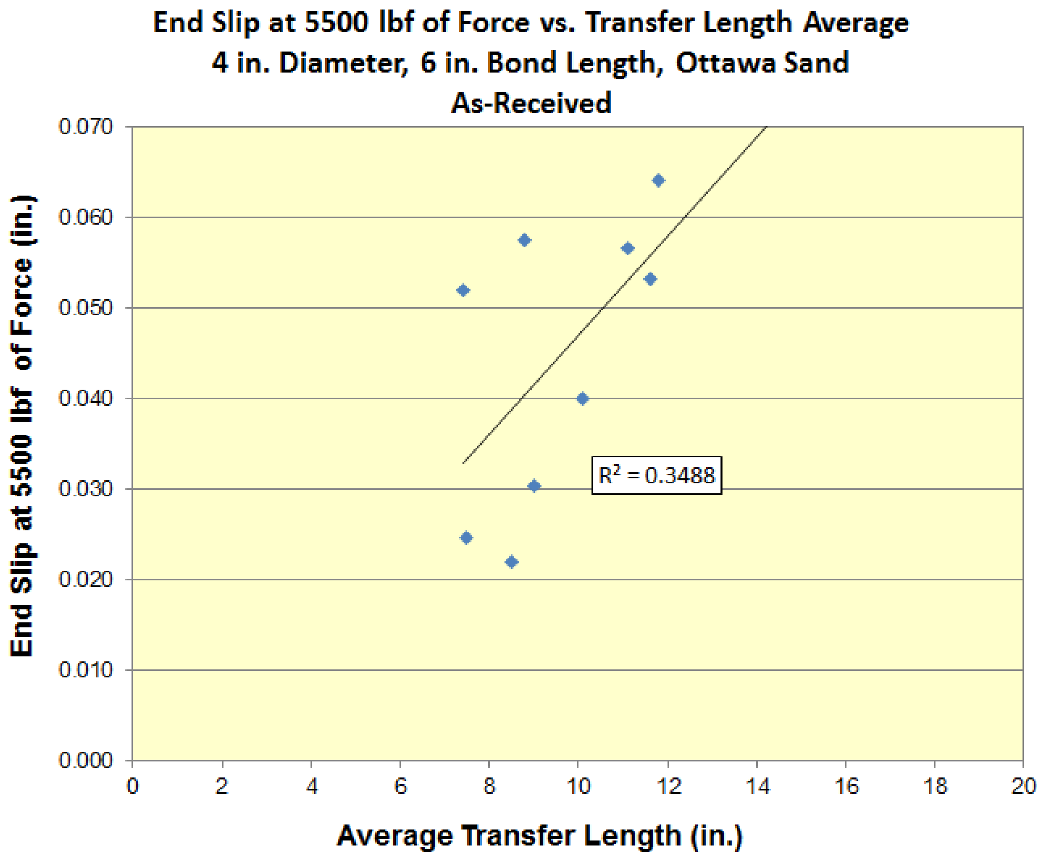


Figure G.19 As-received wires, end slip at 5500 lbf force

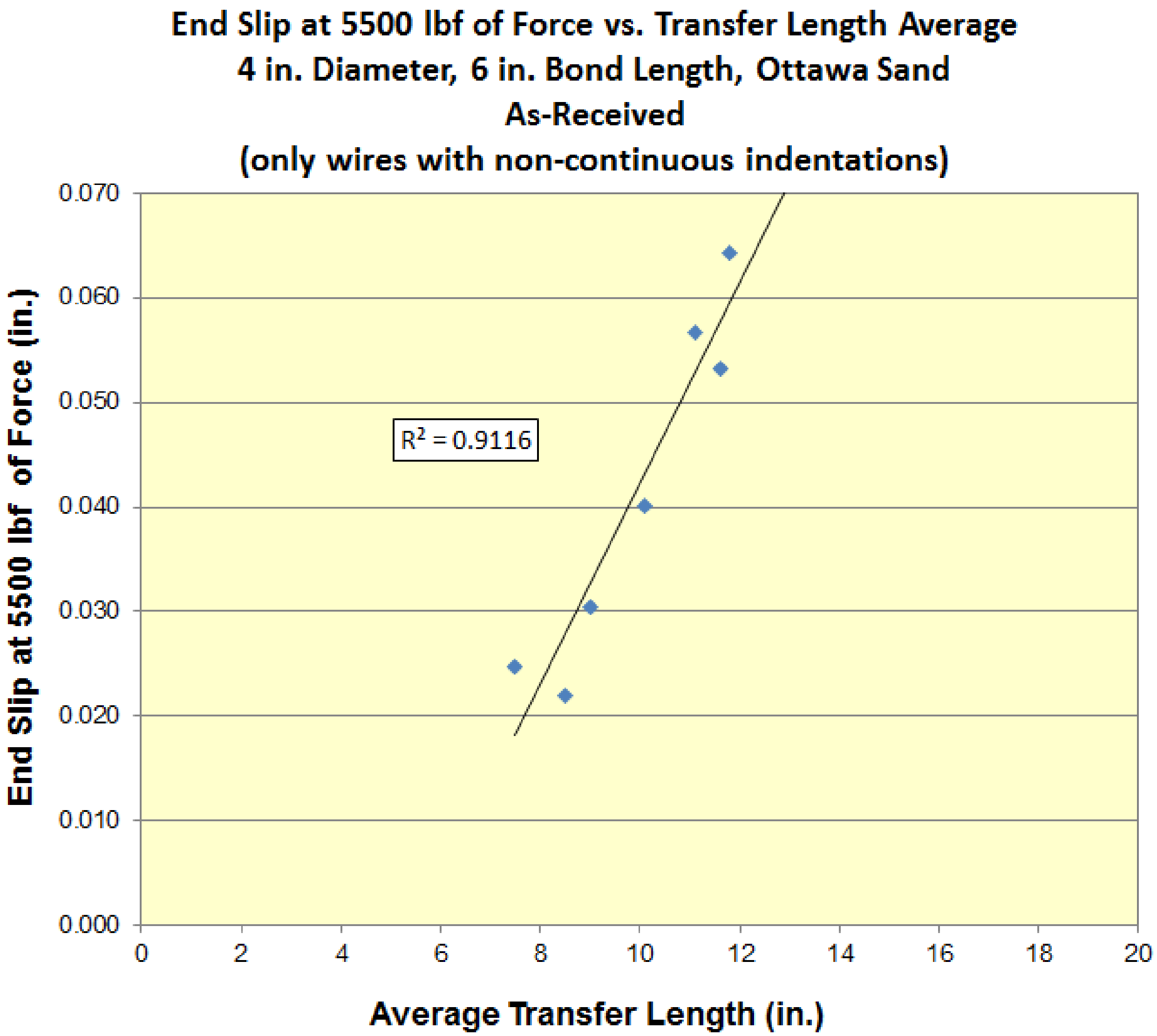
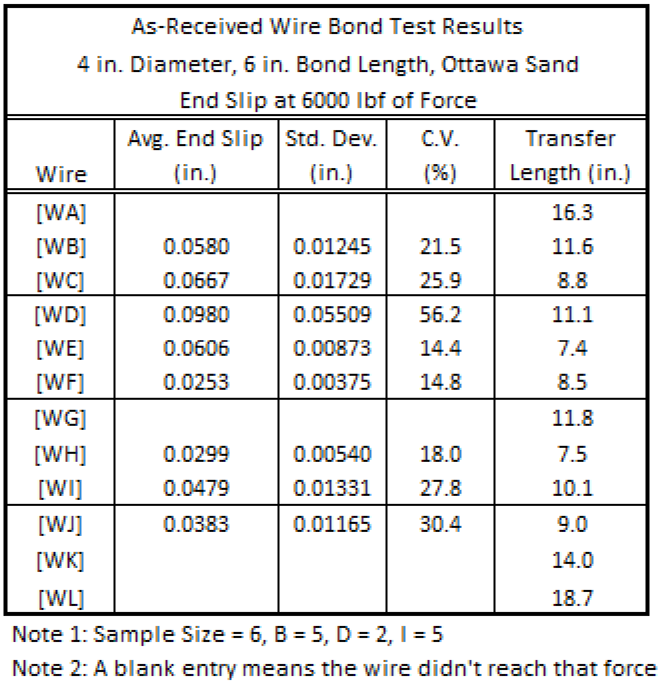


Figure G.20 As-received wires, end slip at 5500 lbf force (individual-indents only)

Table G.11 As-received wires, end slip at 6000 lbf force



As-Received Wire Bond Test Results
4 in. Diameter, 6 in. Bond Length, Ottawa Sand
End Slip at 6000 lbf of Force

Wire	Avg. End Slip (in.)	Std. Dev. (in.)	C.V. (%)	Transfer Length (in.)
[WA]				16.3
[WB]	0.0580	0.01245	21.5	11.6
[WC]	0.0667	0.01729	25.9	8.8
[WD]	0.0980	0.05509	56.2	11.1
[WE]	0.0606	0.00873	14.4	7.4
[WF]	0.0253	0.00375	14.8	8.5
[WG]				11.8
[WH]	0.0299	0.00540	18.0	7.5
[WI]	0.0479	0.01331	27.8	10.1
[WJ]	0.0383	0.01165	30.4	9.0
[WK]				14.0
[WL]				18.7

Note 1: Sample Size = 6, B = 5, D = 2, I = 5

Note 2: A blank entry means the wire didn't reach that force

Figure G.21 As-received wires, end slip at 6000 lbf force

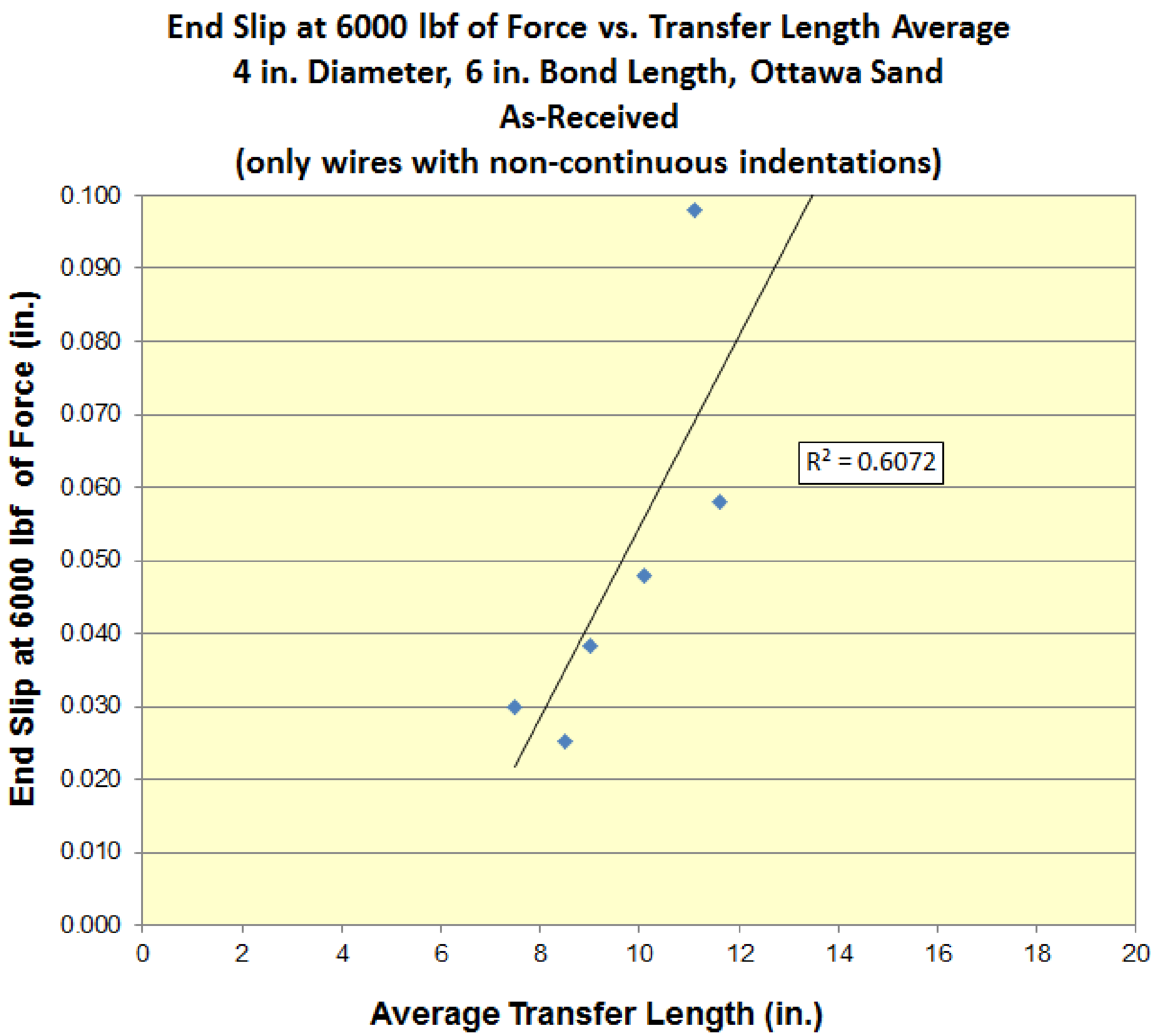


Figure G.22 As-received wires, end slip at 6000 lbf force (individual-indents only)

Appendix H - Lab Phase, Wire; As-Received vs. Cleaned Analysis

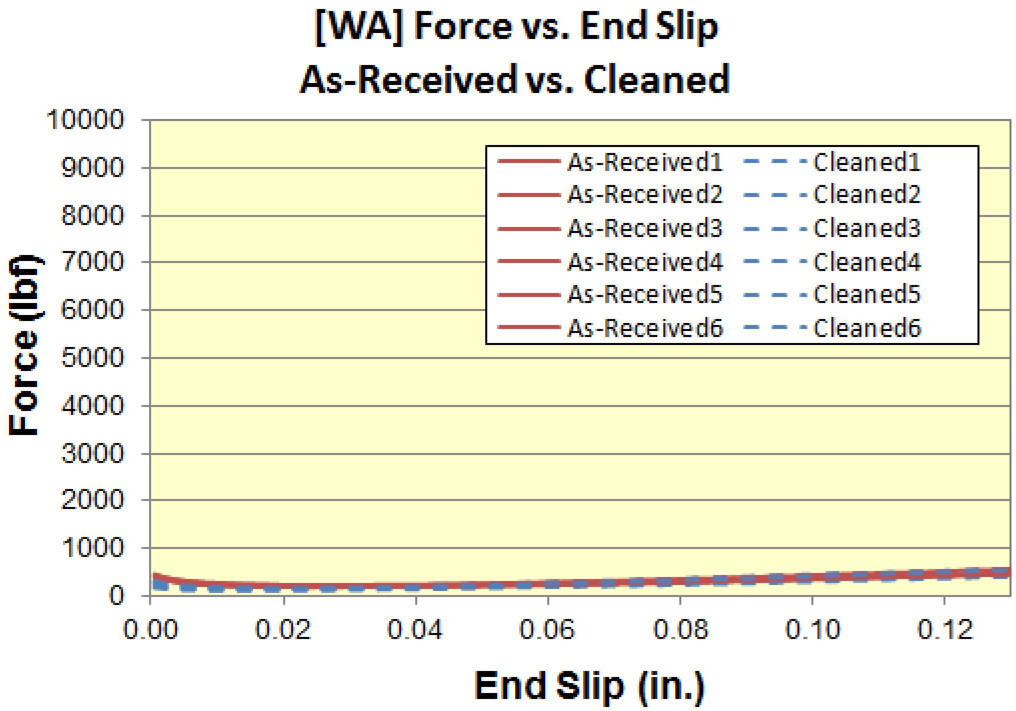


Figure H.1 [WA] force vs. end slip individual graphs, as-received vs. cleaned

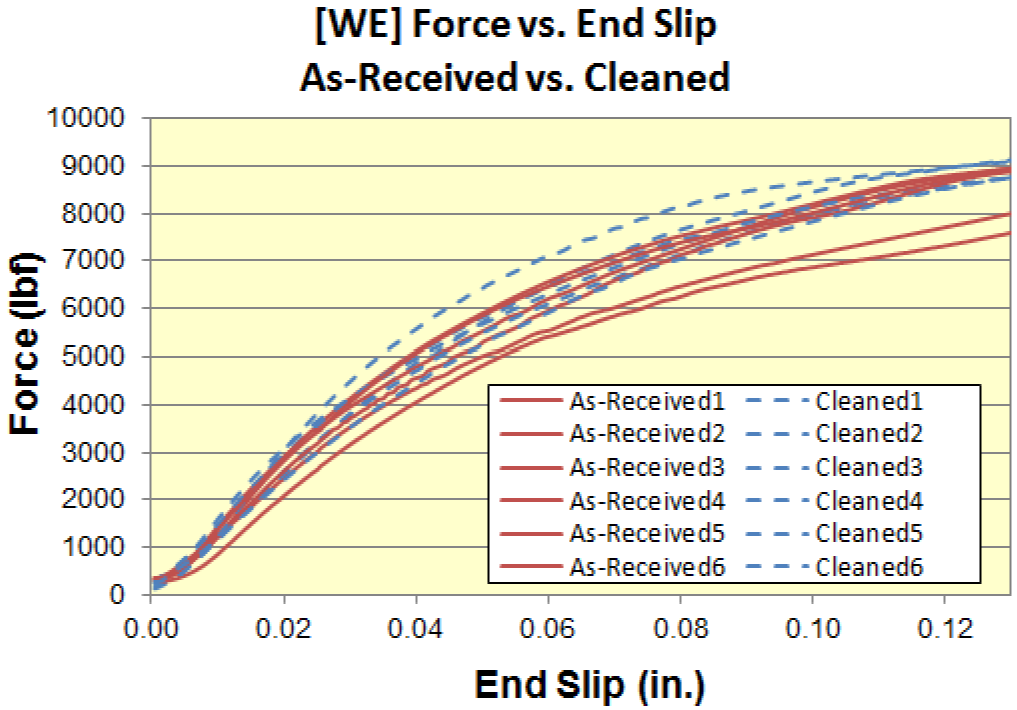


Figure H.2 [WE] force vs. end slip individual graphs, as-received vs. cleaned

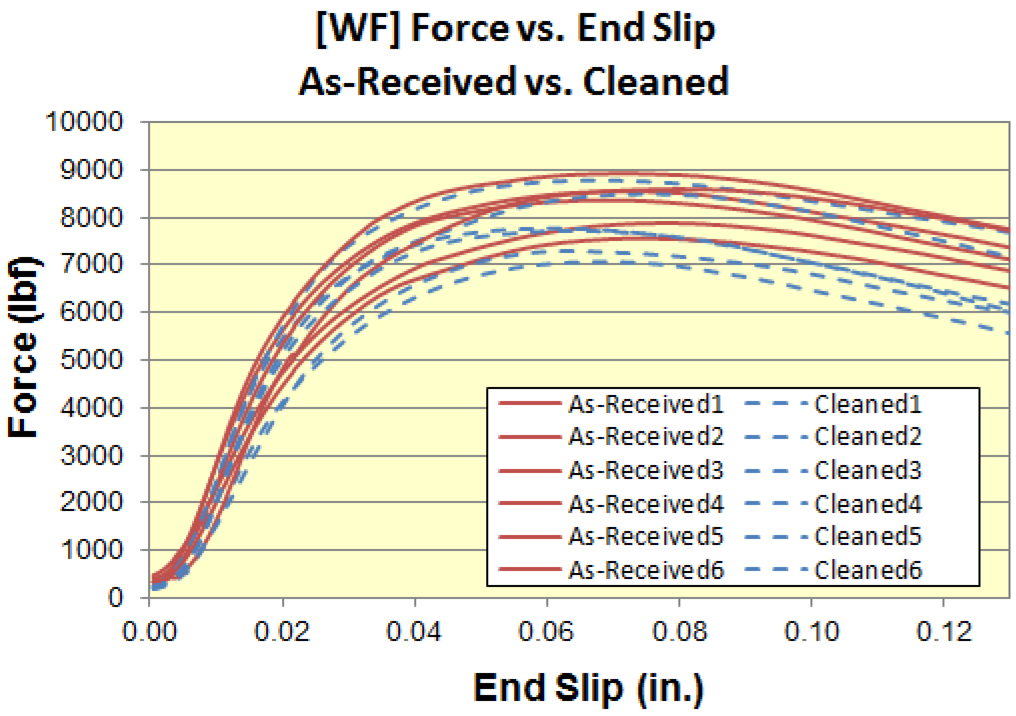


Figure H.3 [WF] force vs. end slip individual graphs, as-received vs. cleaned

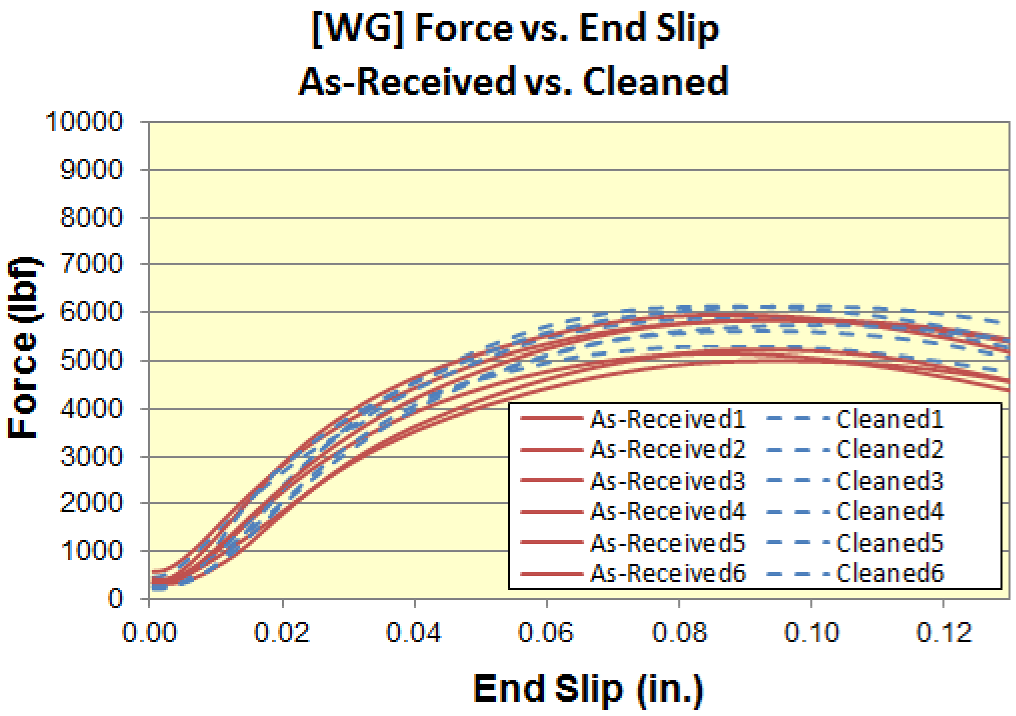


Figure H.4 [WG] force vs. end slip individual graphs, as-received vs. cleaned

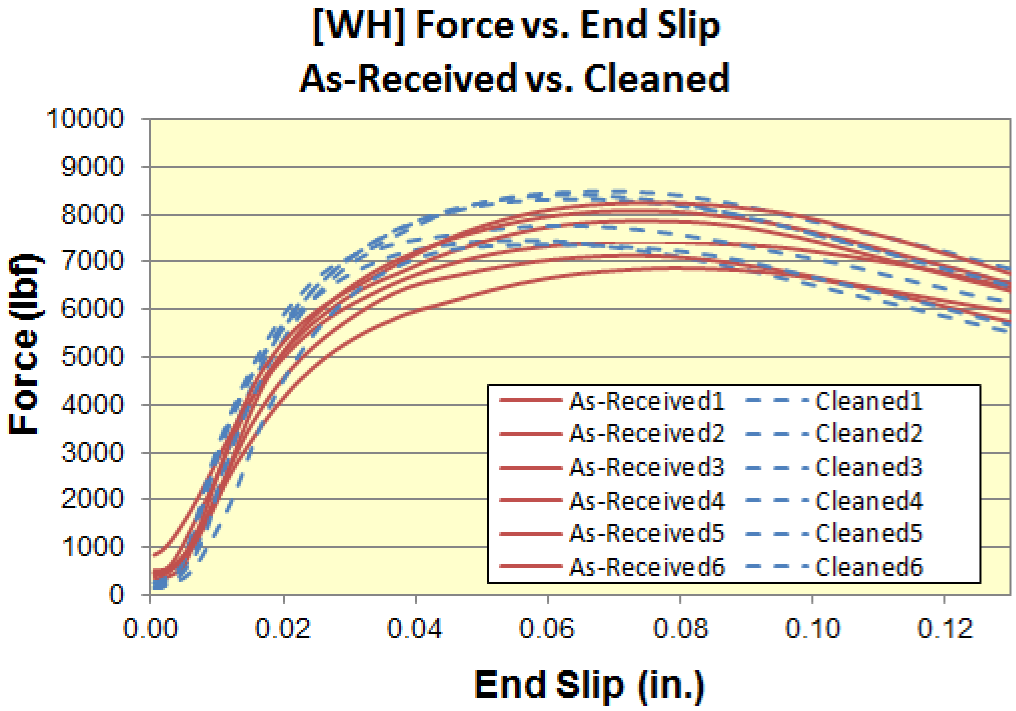


Figure H.5 [WH] force vs. end slip individual graphs, as-received vs. cleaned

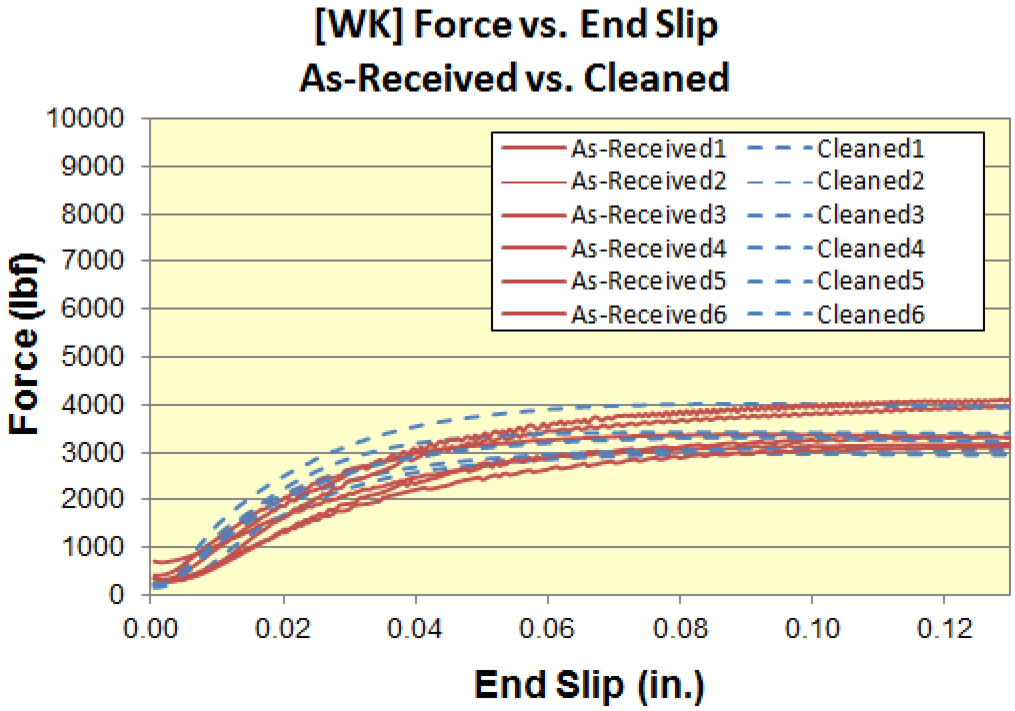


Figure H.6 [WK] force vs. end slip individual graphs, as-received vs. cleaned

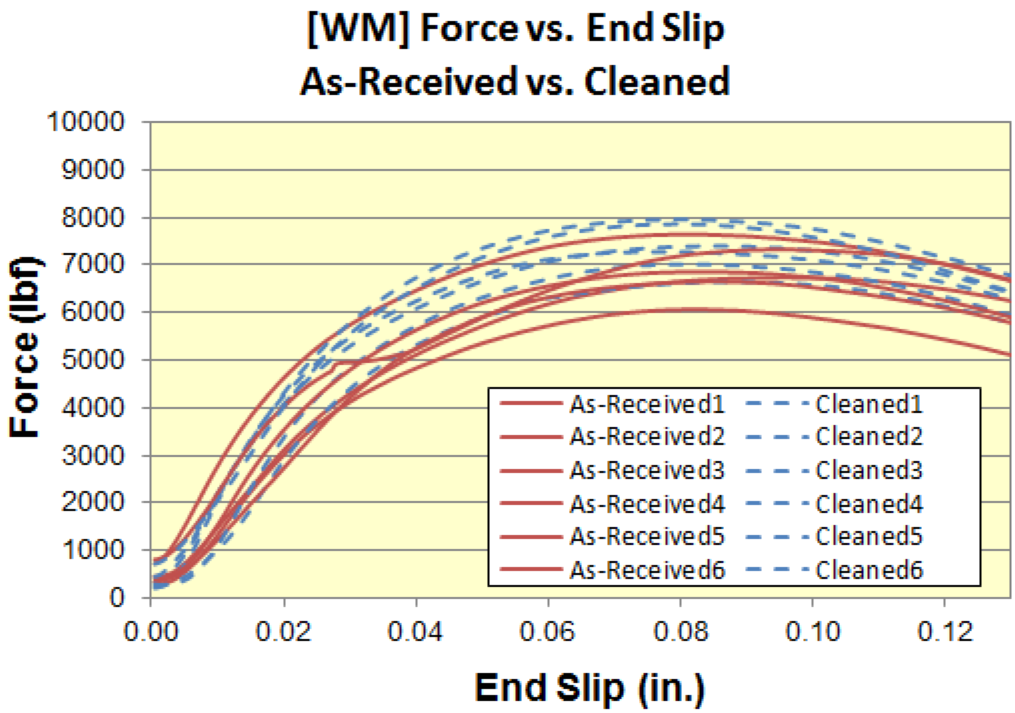


Figure H.7 [WM] force vs. end slip individual graphs, as-received vs. cleaned

Appendix I - Standard Test Method for Evaluating the Bond Quality of 5.32-mm-Diameter Prestressing Wire

1. Scope

This test method describes procedures for determining the bond of 5.32-mm-diameter steel prestressing wires. The bond determined by this test method is stated as the tensile force required to pull the wire through the cured mortar in a cylindrical steel casing. The result of the test is the maximum tensile force measured on the loaded-end of the wire recorded at a free-end slip less than or equal to 0.10 in.

This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Reference Documents

ASTM A881
ASTM C109
ASTM C150
ASTM C192
ASTM C230
ASTM C511
ASTM C778
ASTM C1437

3. Terminology

Bond – the adhesion of wire to mortar or concrete.

Bond breaker – a product wrapped around wire to prevent wire-to-mortar bond over the installed length. Duct tape is commonly used for this purpose.

Mortar – a mixture of cement, fine aggregate, and water.

Wire – all references to wire in this test method shall be assumed to be 5.32-mm-diameter, low-relaxation indented prestressing steel wire conforming to ASTM A881.

Test specimen – an assembly consisting of one steel casing, one sample of wire and mortar.

4. Summary of Test Method

Six samples of 5.32-mm-diameter steel prestressing wire are selected from a single continuous length for testing. Each wire sample is cast into a steel casing with a bonded length of 6-in. A mortar mixture is recommended, but is not prescribed. The fine aggregate source is prescribed, but the cement source is not. Testing on the six specimens begins shortly after the mortar-cube compressive strength reaches 4500 psi and ends before the strength reached 5000 psi. A specified, force-controlled loading rate is applied at the bottom of the wire while continuously monitoring and recording the applied load and free-end slip at the opposite (top) end. The maximum pullout force occurring at an end slip less than or equal to 0.10-in. is recorded as the “test result.” One complete test is comprised of the average of these six specimens.

5. Apparatus

A position transducer – generally a linear variable displacement transducer (LVDT) – with a minimum precision of 0.001-in.

A tensile testing machine with the following functionality:

- Force-controlled loading rate
- Gripping device without torsional restraint. This is commonly accomplished by providing a thrust bearing to allow rotation.
- Rigid testing frame. An example of the frame used for test development is shown in Figure I.2.

6. Sampling of Wire

Samples of wire approximately 20-in. long with be taken from the same coil of prestressing wire. A minimum of six wire specimens are required, but more are permitted.

7. Mortar Requirements

Materials:

- Sand – the sand shall be silica sand from the Ottawa, Illinois region and conforming to ASTM C778. The sand shall come from natural sources. Manufactured sand is not permitted.
- Cement – the cement shall conform to ASTM C150 requirements for Type III cement.
- Water – the water shall be potable.
- Admixtures – admixtures shall not be used.

Mixing procedure:

Mixing procedure will conform to ASTM C192 except no coarse aggregates or admixtures are allowed.

Flow and strength:

- Mortar flow will be measured using the method of ASTM C1437. The flow table used for workability testing must meet the specifications of ASTM C230.
- Mortar strength will be evaluated according to ASTM C109 using 2-in. mortar cubes. Brass molds shall be used. Testing of the pullout specimens may begin after the 2-in. mortar cube compressive strength reaches 4500 psi. If the mortar strength reaches 5000 psi before the conclusion of the test, then the test is invalid and must be performed again.

Mix proportions:

The proportions and bath weights listed are recommended, but not prescribed. Any mixture conforming to the flow and strength requirements listed in the previous sub-section are allowed.

Table I.1 shows a mortar with a water-to-cement ratio (w/c) of 0.425 and a sand-to-cement (s/c) ratio of 2.0.

Table I.1 Recommended batch weights

Material	Batch Weights (lbf)
Ottawa Sand	47.9
Type III Cement	23.9
Water	10.2
Total	**82.0**

8. Preparation of Test Specimens

Materials:

- Wire samples – requirements as defined in Section 6.
- Mortar – requirements as defined in Section 7.
- Bottom bond breaker – a 1-in. wide ± 0.125-in. piece of duct tape shall be used as a bottom bond breaker. The length of bond breaker should be no less than 5-in. before application. The bond breaker shall be wrapped around the wire snugly.
- Top bond breaker – a 2-in. wide ± 0.125-in. piece of duct tape shall be used as a top bond breaker. The length of bond breaker should be no less than 3-in. before application. The bond breaker shall be wrapped around the wire snugly. The top bond breaker shall extend past the top mortar surface approximately 1 in. to ensure the exact bond length desired in case of settlement.
- Steel casing – Each individual wire specimen shall be cast in a 4-in.-outer-diameter steel tube, approximately 1/8-in. wall thickness (11 gage), and a total length of 8 in. A 6-in. x 6-in. x 3/16-in. thick steel plate is tack welded to the bottom of the tube. The remaining contact surface shall be caulked to prevent any leakage. A schematic of the wire pullout specimen is shown in Figure I.1. The bottom plate shall have a 1/4-in.-diameter hole drilled in the center to allow the steel wire to pass through.

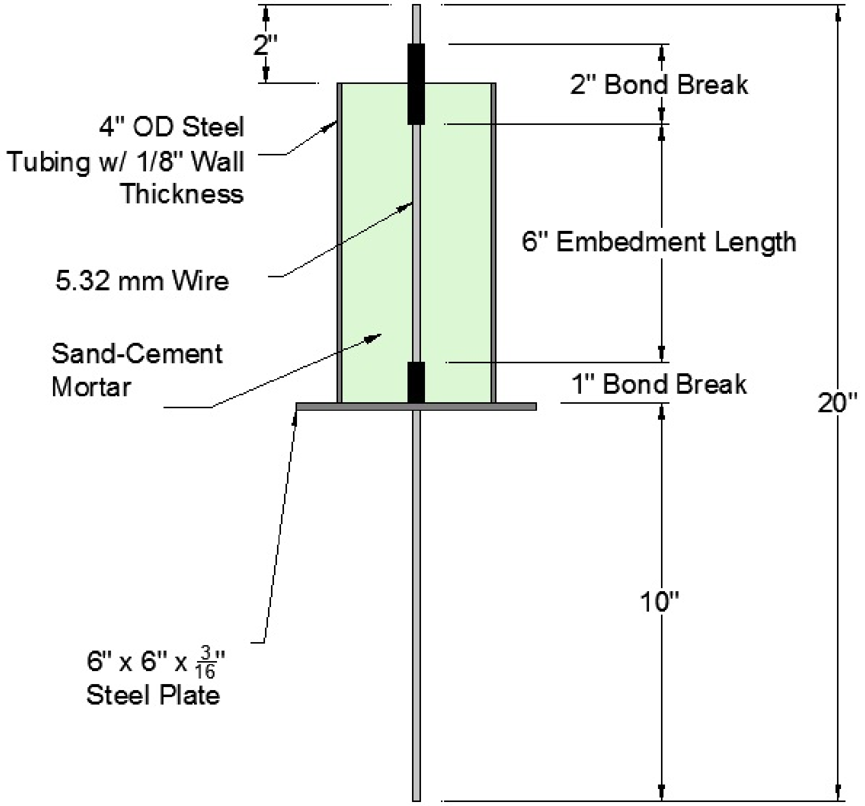


Figure I.1 Schematic of wire pullout test specimen

- Specimen assembly – Each wire specimen will be cast into a steel casing in the vertical position. The wires shall be held centered (concentrically ± 1/8-in.) in the steel tube using an additional fixture and rebar ties. The additional fixture can be removed after the mortar has cured and prior to testing.
- Consolidation - The pullout specimens shall be filled in two approximately equal lifts and consolidated using a wand-type vibrator between each lift. The first lift should be approximately 50% and the second lift approximately 40%. The remaining 10% of mortar shall be added and smoothed using a hand trowel.
- Curing - The pullout test specimens and 2-in. mortar cubes shall be cured at a relative humidity of the specimens and cubes greater than or equal to 90% for the duration of curing. The specimens and cubes shall be stored in a temperature- and humidity-controlled room maintained at a temperature of 73.5 ± 3.5 ^{o}F and a relative humidity above 50%. These parameters can be accomplished without the

use of a moist room or closet. As such, a moist room or closet is allowed, but not required. The test specimens shall be cured in an environment free of vibrations.

9. Test Set-up

- Test frame – the specimens shall be tested in a frame as described in Section 5. A schematic of the test frame used for test development is shown in Figure I.2.

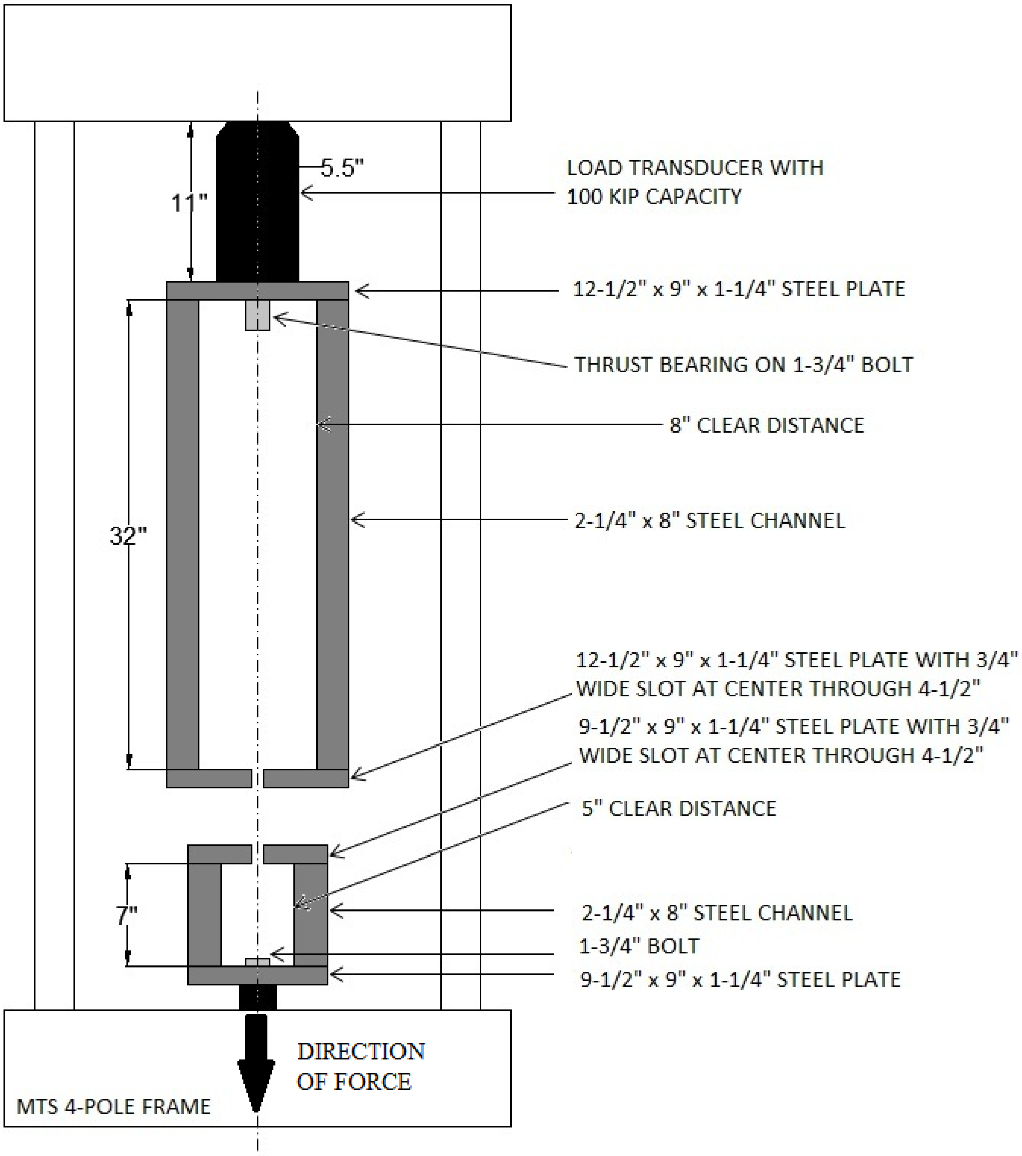


Figure I.2 Schematic of pullout load frame used for test development

- Free-end slip measurement – A position transducer, generally a linear variable displacement transducer (LVDT), shall be installed to measure the free-end slip of the wire relative to the hardened mortar surface. The position transducer shall be centered on the wire. A picture of the setup used for test development is shown in Figure I.3.

Figure I.3 LVDT and magnetic base setup used for test development

- Wire gripping – the wire shall be gripped by a chucking device. The free length between the bottom of the plate of the steel casing and the top of the chucking device shall be a minimum of 7-in. The test shall be free from torsional restraint.

10. Test Procedure

- Test start – the test specimens shall be removed from the temperature- and humidity-controlled room and testing may begin once the mortar strength reaches 4500 psi as evaluated by the 2-in. mortar cubes. This mortar strength is defined as the average of at least two individual 2-in. mortar cubes.
- Mortar strength – the mortar strength shall be tested at the beginning of the test and at the end of the test. Technicians are encouraged to monitor the mortar strength intermittently by using an extra mortar cubes that were made.
- Force rate – load shall be applied to the strand by displacement of the chucking device. A force-controlled rate of 2000 lbf/min. ± 100 lbf/min. shall be maintained after the chuck has been initially seated.
- Test result – The maximum pullout force occurring at an end slip less than or equal to 0.10-in. shall be recorded. This force should be rounded to the nearest 10 lbf.
- Acceptance of test result – if the hardened mortar exhibits cracking visible to normal of corrected vision in two or more of the six test specimens, the entire batch of six specimens shall be discarded and new specimens prepared.

11. Report

The following items shall be reported concisely:

- Identification of the wire tested (that is, coil number, manufacturer, original manufacture date, manufacture location).
- Size and indentation pattern of wire.
- Date and time of casting. Casting time is reported as the time the mortar is finished being mixed. Casting time can be reported to the nearest 15 minutes.
- Batch weights and origin of constituent materials.
- Flow table value.
- Concrete temperature at the time mortar is finished mixing.
- Date and time of testing. Time of testing is reported as the time the load begins to be applied to the specimen. Testing time can be reported to the nearest minute.

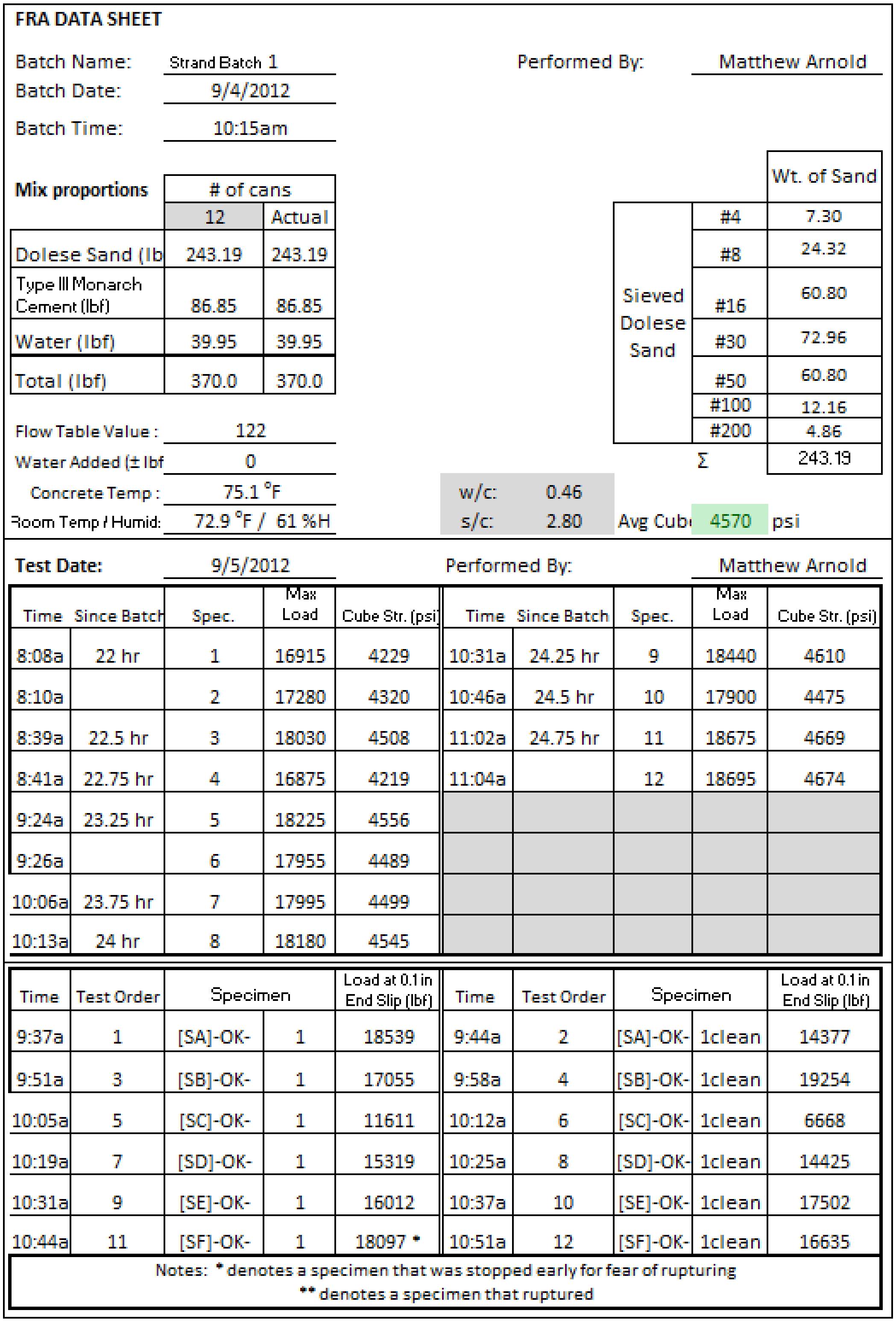
- Six individual test results.
- Average test result.
- Individual mortar cube compressive strengths and times performed. Time performed should be reported both as time of day (to the nearest minute) and time since mortar was batched (to the nearest 30 minutes).
- Average of beginning and ending mortar strengths.

12. Precision and Bias

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.

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

Appendix J - Lab Phase, Strand; As-Received and Cleaned Batch Summaries



FRA DATA SHEET

Batch Name: Strand Batch 1
Batch Date: 9/4/2012
Batch Time: 10:15am
Performed By: Matthew Arnold

Mix proportions	# of cans	
	12	Actual
Dolese Sand (lb	243.19	243.19
Type III Monarch Cement (lbf)	86.85	86.85
Water (lbf)	39.95	39.95
Total (lbf)	370.0	370.0

		Wt. of Sand
Sieved Dolese Sand	#4	7.30
	#8	24.32
	#16	60.80
	#30	72.96
	#50	60.80
	#100	12.16
	#200	4.86
	Σ	243.19

Flow Table Value : 122
Water Added (± lbf 0
Concrete Temp : 75.1 °F
Room Temp / Humid: 72.9 °F / 61 %H

w/c: 0.46
s/c: 2.80
Avg Cub 4570 psi

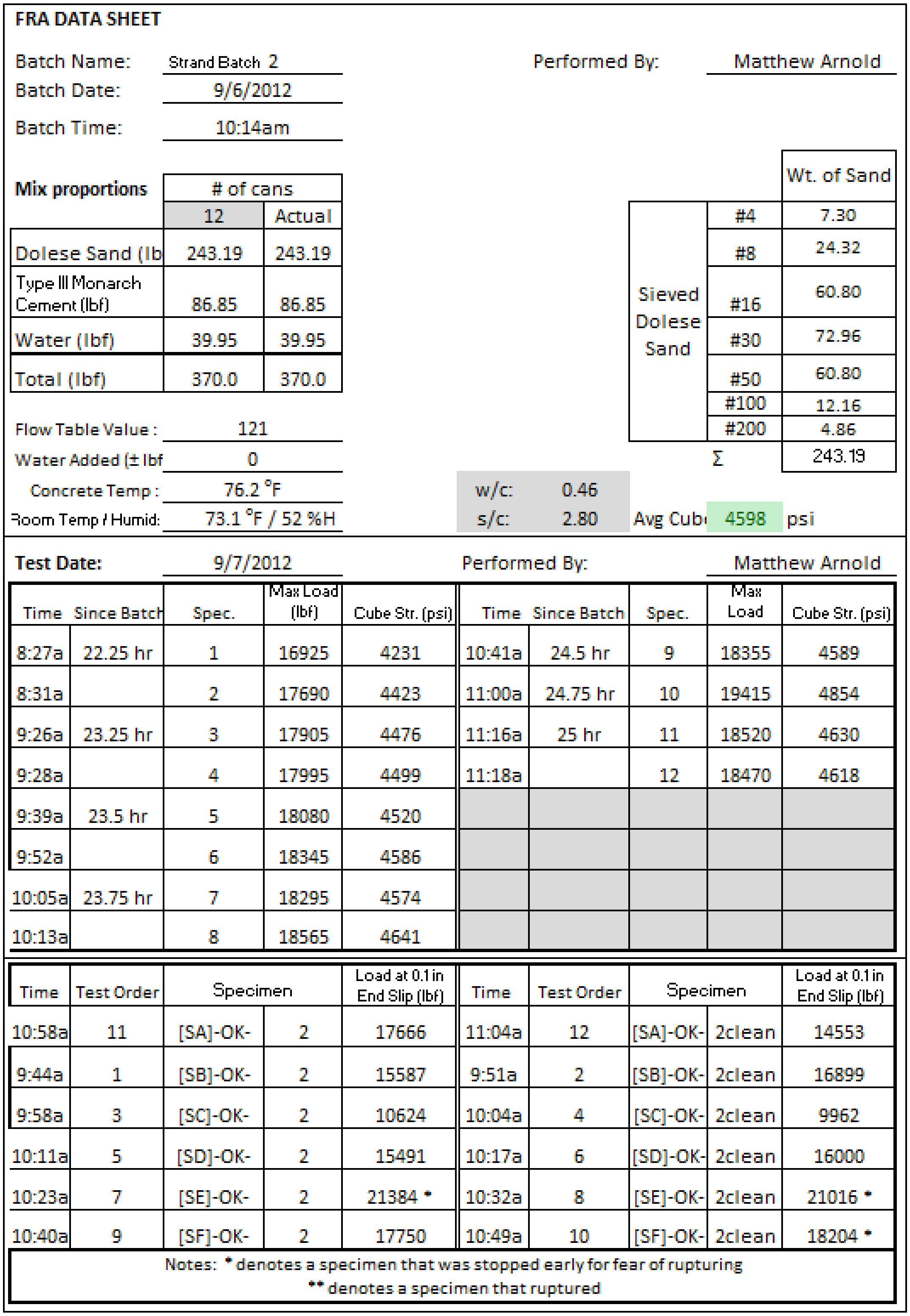
Test Date: 9/5/2012
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:08a	22 hr	1	16915	4229	10:31a	24.25 hr	9	18440	4610
8:10a		2	17280	4320	10:46a	24.5 hr	10	17900	4475
8:39a	22.5 hr	3	18030	4508	11:02a	24.75 hr	11	18675	4669
8:41a	22.75 hr	4	16875	4219	11:04a		12	18695	4674
9:24a	23.25 hr	5	18225	4556					
9:26a		6	17955	4489					
10:06a	23.75 hr	7	17995	4499					
10:13a	24 hr	8	18180	4545					

Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)	Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)
9:37a	1	[SA]-OK-	1	18539	9:44a	2	[SA]-OK-	1clean	14377
9:51a	3	[SB]-OK-	1	17055	9:58a	4	[SB]-OK-	1clean	19254
10:05a	5	[SC]-OK-	1	11611	10:12a	6	[SC]-OK-	1clean	6668
10:19a	7	[SD]-OK-	1	15319	10:25a	8	[SD]-OK-	1clean	14425
10:31a	9	[SE]-OK-	1	16012	10:37a	10	[SE]-OK-	1clean	17502
10:44a	11	[SF]-OK-	1	18097 *	10:51a	12	[SF]-OK-	1clean	16635

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure J.1 As-received and cleaned strands, batch summary #1 (16 in. bond length)



FRA DATA SHEET

Batch Name: Strand Batch 2

Batch Date: 9/6/2012

Batch Time: 10:14am

Performed By: Matthew Arnold

Mix proportions	# of cans	
	12	Actual
Dolese Sand (lb	243.19	243.19
Type III Monarch Cement (lbf)	86.85	86.85
Water (lbf)	39.95	39.95
Total (lbf)	370.0	370.0

		Wt. of Sand
Sieved Dolese Sand	#4	7.30
	#8	24.32
	#16	60.80
	#30	72.96
	#50	60.80
	#100	12.16
	#200	4.86
	Σ	243.19

Flow Table Value : 121

Water Added (± lbf 0

Concrete Temp : 76.2 °F

Room Temp / Humid: 73.1 °F / 52 %H

w/c: 0.46

s/c: 2.80

Avg Cub 4598 psi

Test Date: 9/7/2012

Performed By: Matthew Arnold

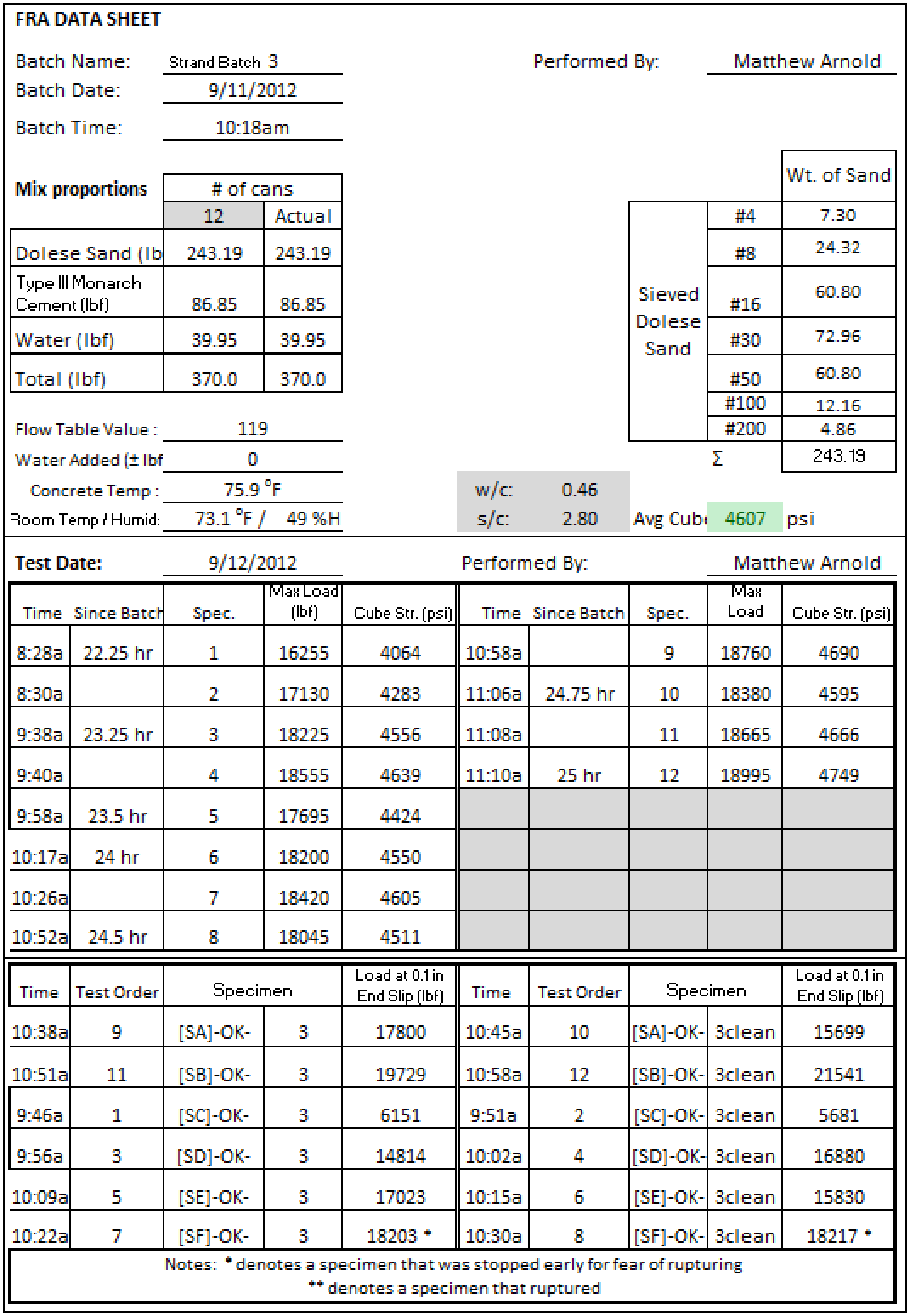
Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:27a	22.25 hr	1	16925	4231	10:41a	24.5 hr	9	18355	4589
8:31a		2	17690	4423	11:00a	24.75 hr	10	19415	4854
9:26a	23.25 hr	3	17905	4476	11:16a	25 hr	11	18520	4630
9:28a		4	17995	4499	11:18a		12	18470	4618
9:39a	23.5 hr	5	18080	4520					
9:52a		6	18345	4586					
10:05a	23.75 hr	7	18295	4574					
10:13a		8	18565	4641					

Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)	Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)
10:58a	11	[SA]-OK-	2	17666	11:04a	12	[SA]-OK-	2clean	14553
9:44a	1	[SB]-OK-	2	15587	9:51a	2	[SB]-OK-	2clean	16899
9:58a	3	[SC]-OK-	2	10624	10:04a	4	[SC]-OK-	2clean	9962
10:11a	5	[SD]-OK-	2	15491	10:17a	6	[SD]-OK-	2clean	16000
10:23a	7	[SE]-OK-	2	21384 *	10:32a	8	[SE]-OK-	2clean	21016 *
10:40a	9	[SF]-OK-	2	17750	10:49a	10	[SF]-OK-	2clean	18204 *

Notes: * denotes a specimen that was stopped early for fear of rupturing

** denotes a specimen that ruptured

Figure J.2 As-received and cleaned strands, batch summary #2 (16 in. bond length)



FRA DATA SHEET

Batch Name: Strand Batch 3

Performed By: Matthew Arnold

Batch Date: 9/11/2012

Batch Time: 10:18am

Mix proportions	# of cans	
	12	Actual
Dolese Sand (Ib	243.19	243.19
Type III Monarch Cement (lbf)	86.85	86.85
Water (lbf)	39.95	39.95
Total (lbf)	370.0	370.0

		Wt. of Sand
Sieved Dolese Sand	#4	7.30
	#8	24.32
	#16	60.80
	#30	72.96
	#50	60.80
	#100	12.16
	#200	4.86
	Σ	243.19

Flow Table Value : 119

Water Added (± lbf 0

Concrete Temp : 75.9 °F

Room Temp / Humid: 73.1 °F / 49 %H

w/c: 0.46

s/c: 2.80

Avg Cub 4607 psi

Test Date: 9/12/2012

Performed By: Matthew Arnold

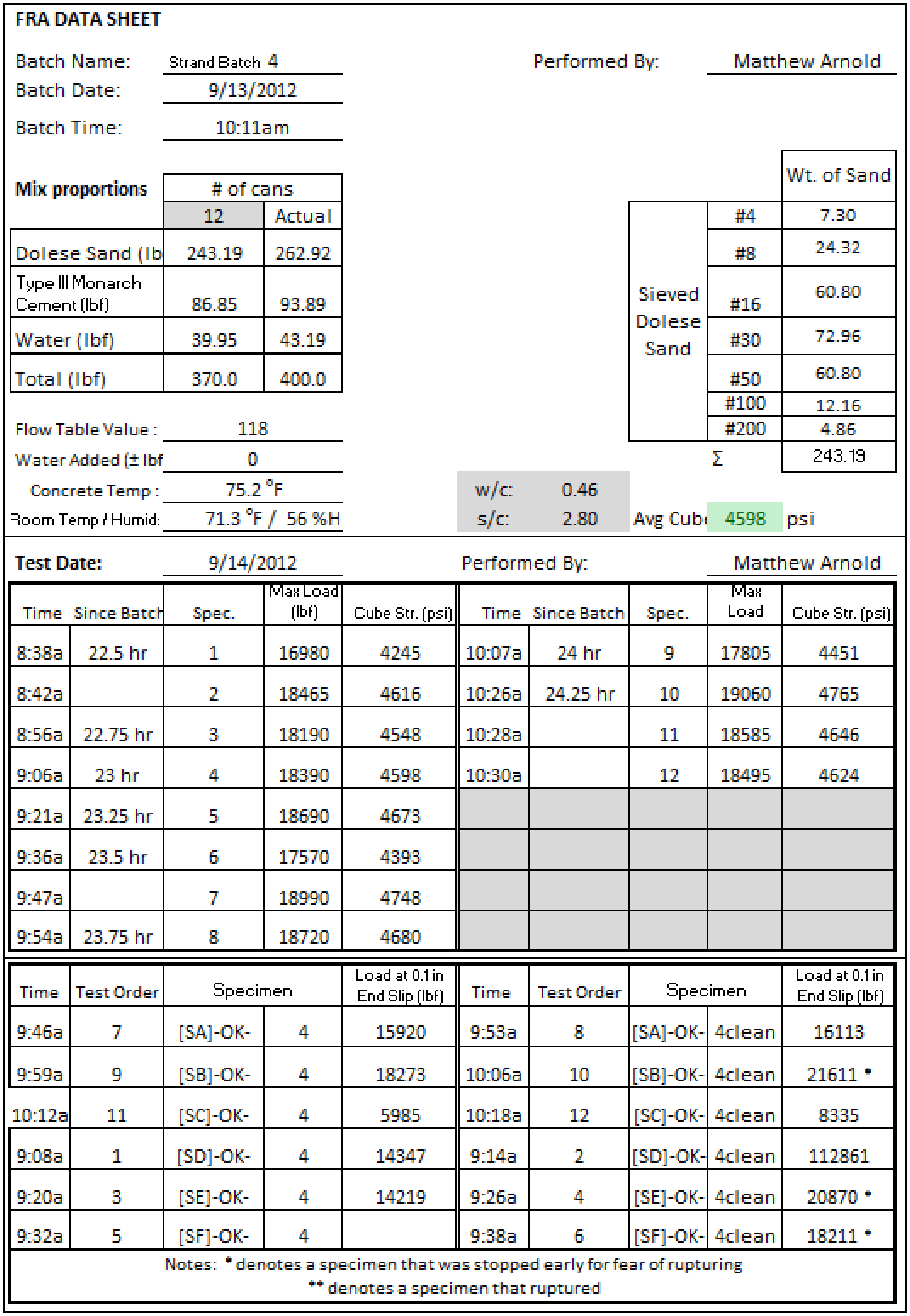
Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:28a	22.25 hr	1	16255	4064	10:58a		9	18760	4690
8:30a		2	17130	4283	11:06a	24.75 hr	10	18380	4595
9:38a	23.25 hr	3	18225	4556	11:08a		11	18665	4666
9:40a		4	18555	4639	11:10a	25 hr	12	18995	4749
9:58a	23.5 hr	5	17695	4424					
10:17a	24 hr	6	18200	4550					
10:26a		7	18420	4605					
10:52a	24.5 hr	8	18045	4511					

Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)	Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)
10:38a	9	[SA]-OK-	3	17800	10:45a	10	[SA]-OK-	3clean	15699
10:51a	11	[SB]-OK-	3	19729	10:58a	12	[SB]-OK-	3clean	21541
9:46a	1	[SC]-OK-	3	6151	9:51a	2	[SC]-OK-	3clean	5681
9:56a	3	[SD]-OK-	3	14814	10:02a	4	[SD]-OK-	3clean	16880
10:09a	5	[SE]-OK-	3	17023	10:15a	6	[SE]-OK-	3clean	15830
10:22a	7	[SF]-OK-	3	18203 *	10:30a	8	[SF]-OK-	3clean	18217 *

Notes: * denotes a specimen that was stopped early for fear of rupturing

** denotes a specimen that ruptured

Figure J.3 As-received and cleaned strands, batch summary #3 (16 in. bond length)



FRA DATA SHEET

Batch Name: Strand Batch 4

Performed By: Matthew Arnold

Batch Date: 9/13/2012

Batch Time: 10:11am

Mix proportions	# of cans	
	12	Actual
Dolese Sand (lb	243.19	262.92
Type III Monarch Cement (lbf)	86.85	93.89
Water (lbf)	39.95	43.19
Total (lbf)	370.0	400.0

		Wt. of Sand
Sieved Dolese Sand	#4	7.30
	#8	24.32
	#16	60.80
	#30	72.96
	#50	60.80
	#100	12.16
	#200	4.86
	Σ	243.19

Flow Table Value : 118

Water Added (± lbf 0

Concrete Temp : 75.2 °F

Room Temp / Humid: 71.3 °F / 56 %H

w/c: 0.46

s/c: 2.80

Avg Cub 4598 psi

Test Date: 9/14/2012

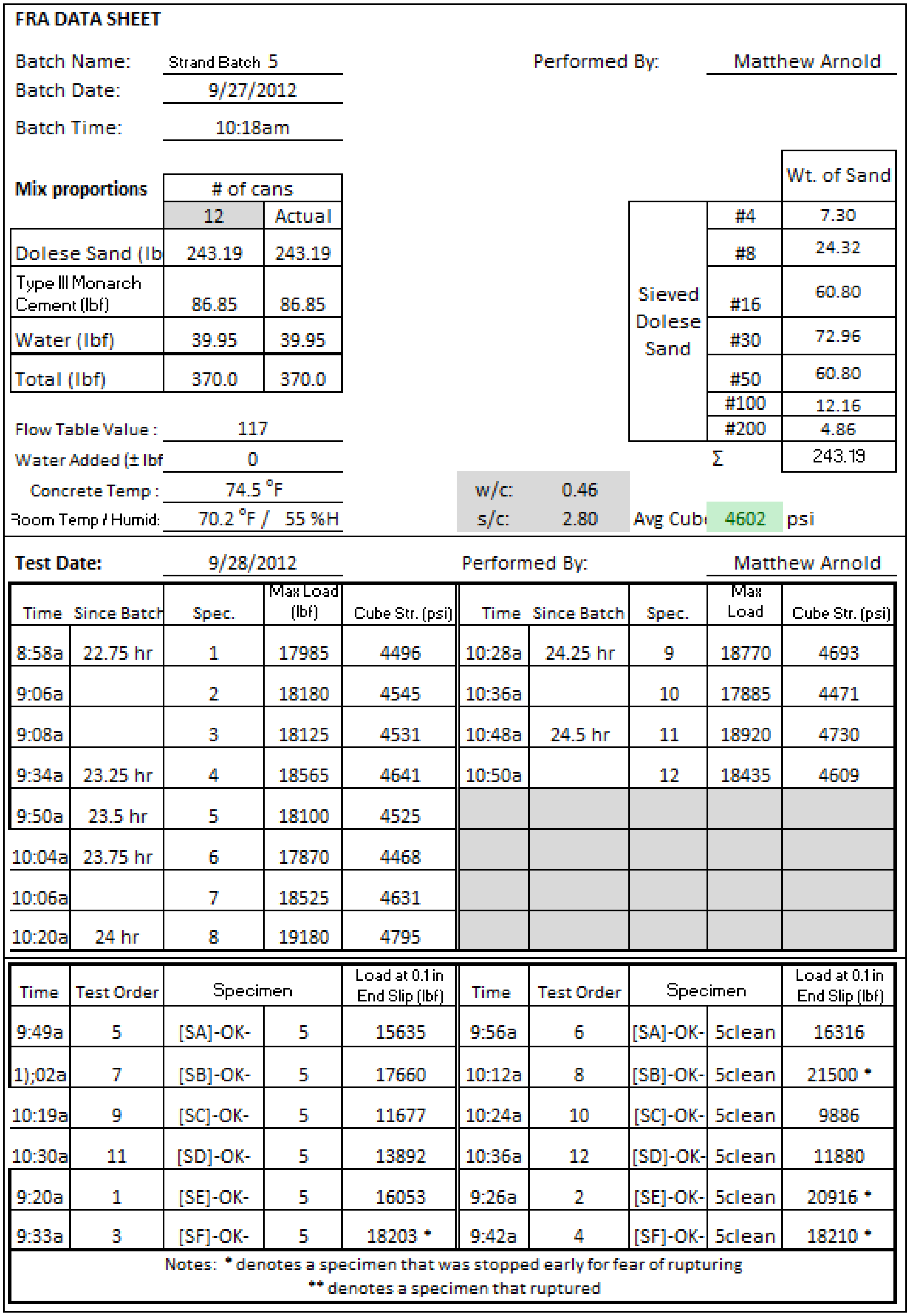
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:38a	22.5 hr	1	16980	4245	10:07a	24 hr	9	17805	4451
8:42a		2	18465	4616	10:26a	24.25 hr	10	19060	4765
8:56a	22.75 hr	3	18190	4548	10:28a		11	18585	4646
9:06a	23 hr	4	18390	4598	10:30a		12	18495	4624
9:21a	23.25 hr	5	18690	4673					
9:36a	23.5 hr	6	17570	4393					
9:47a		7	18990	4748					
9:54a	23.75 hr	8	18720	4680					

Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)	Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)
9:46a	7	[SA]-OK-	4	15920	9:53a	8	[SA]-OK-	4clean	16113
9:59a	9	[SB]-OK-	4	18273	10:06a	10	[SB]-OK-	4clean	21611 *
10:12a	11	[SC]-OK-	4	5985	10:18a	12	[SC]-OK-	4clean	8335
9:08a	1	[SD]-OK-	4	14347	9:14a	2	[SD]-OK-	4clean	112861
9:20a	3	[SE]-OK-	4	14219	9:26a	4	[SE]-OK-	4clean	20870 *
9:32a	5	[SF]-OK-	4		9:38a	6	[SF]-OK-	4clean	18211 *

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure J.4 As-received and cleaned strands, batch summary #4 (16 in. bond length)



FRA DATA SHEET

Batch Name: Strand Batch 5
Performed By: Matthew Arnold
Batch Date: 9/27/2012
Batch Time: 10:18am

Mix proportions	# of cans	
	12	Actual
Dolese Sand (lb	243.19	243.19
Type III Monarch Cement (lbf)	86.85	86.85
Water (lbf)	39.95	39.95
Total (lbf)	370.0	370.0

		Wt. of Sand
Sieved Dolese Sand	#4	7.30
	#8	24.32
	#16	60.80
	#30	72.96
	#50	60.80
	#100	12.16
	#200	4.86
	Σ	243.19

Flow Table Value : 117
Water Added (± lbf 0
Concrete Temp : 74.5 °F
Room Temp / Humid: 70.2 °F / 55 %H
w/c: 0.46
s/c: 2.80
Avg Cub 4602 psi

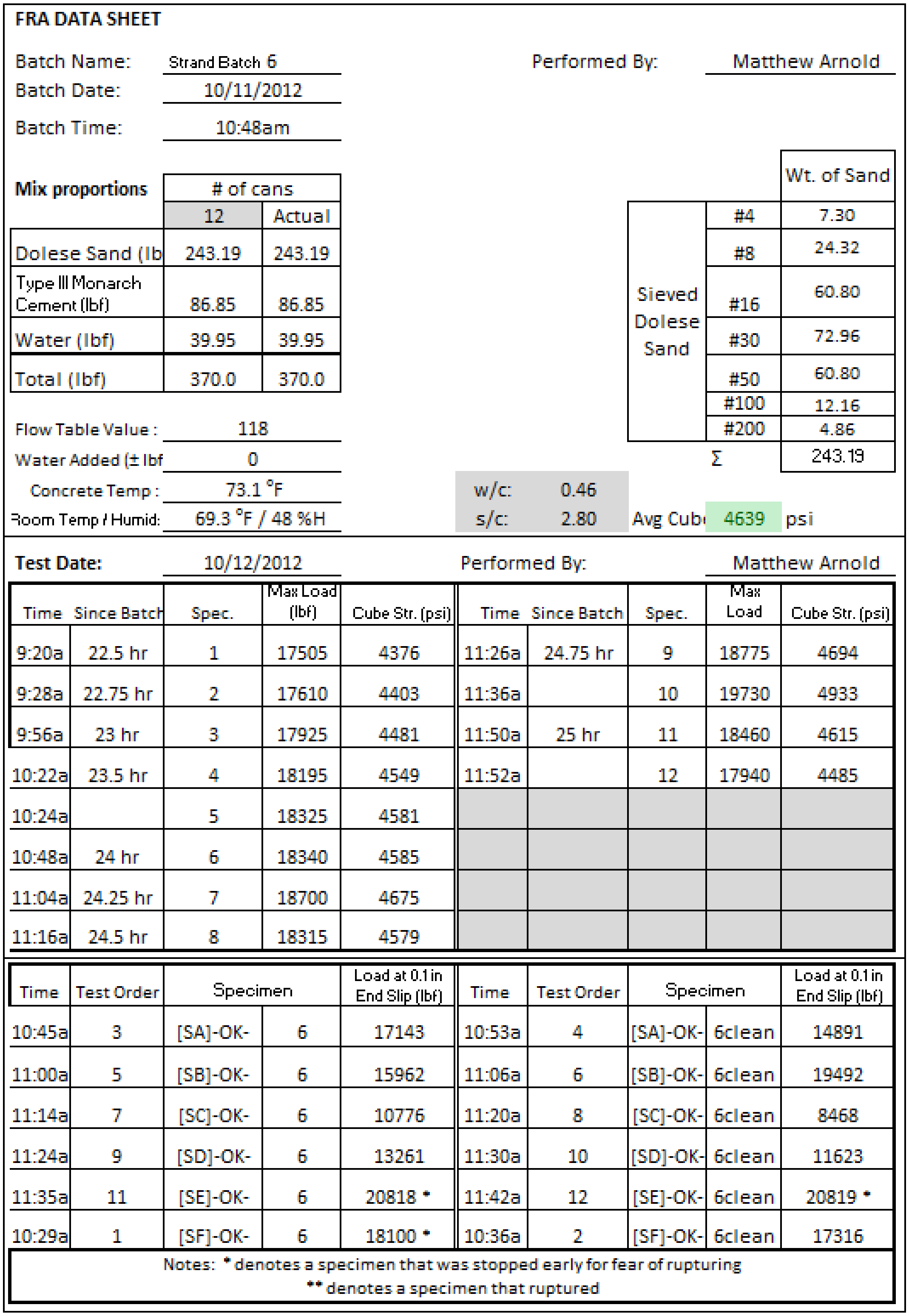
Test Date: 9/28/2012
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:58a	22.75 hr	1	17985	4496	10:28a	24.25 hr	9	18770	4693
9:06a		2	18180	4545	10:36a		10	17885	4471
9:08a		3	18125	4531	10:48a	24.5 hr	11	18920	4730
9:34a	23.25 hr	4	18565	4641	10:50a		12	18435	4609
9:50a	23.5 hr	5	18100	4525					
10:04a	23.75 hr	6	17870	4468					
10:06a		7	18525	4631					
10:20a	24 hr	8	19180	4795					

Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)	Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)
9:49a	5	[SA]-OK-	5	15635	9:56a	6	[SA]-OK-	5clean	16316
1);02a	7	[SB]-OK-	5	17660	10:12a	8	[SB]-OK-	5clean	21500 *
10:19a	9	[SC]-OK-	5	11677	10:24a	10	[SC]-OK-	5clean	9886
10:30a	11	[SD]-OK-	5	13892	10:36a	12	[SD]-OK-	5clean	11880
9:20a	1	[SE]-OK-	5	16053	9:26a	2	[SE]-OK-	5clean	20916 *
9:33a	3	[SF]-OK-	5	18203 *	9:42a	4	[SF]-OK-	5clean	18210 *

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure J.5 As-received and cleaned strands, batch summary #5 (16 in. bond length)



FRA DATA SHEET

Batch Name: Strand Batch 6

Performed By: Matthew Arnold

Batch Date: 10/11/2012

Batch Time: 10:48am

Mix proportions	# of cans	
	12	Actual
Dolese Sand (lb	243.19	243.19
Type III Monarch Cement (lbf)	86.85	86.85
Water (lbf)	39.95	39.95
Total (lbf)	370.0	370.0

		Wt. of Sand
Sieved Dolese Sand	#4	7.30
	#8	24.32
	#16	60.80
	#30	72.96
	#50	60.80
	#100	12.16
	#200	4.86
	Σ	243.19

Flow Table Value : 118

Water Added (± lbf 0

Concrete Temp : 73.1 °F

Room Temp / Humid: 69.3 °F / 48 %H

w/c: 0.46

s/c: 2.80

Avg Cub 4639 psi

Test Date: 10/12/2012

Performed By: Matthew Arnold

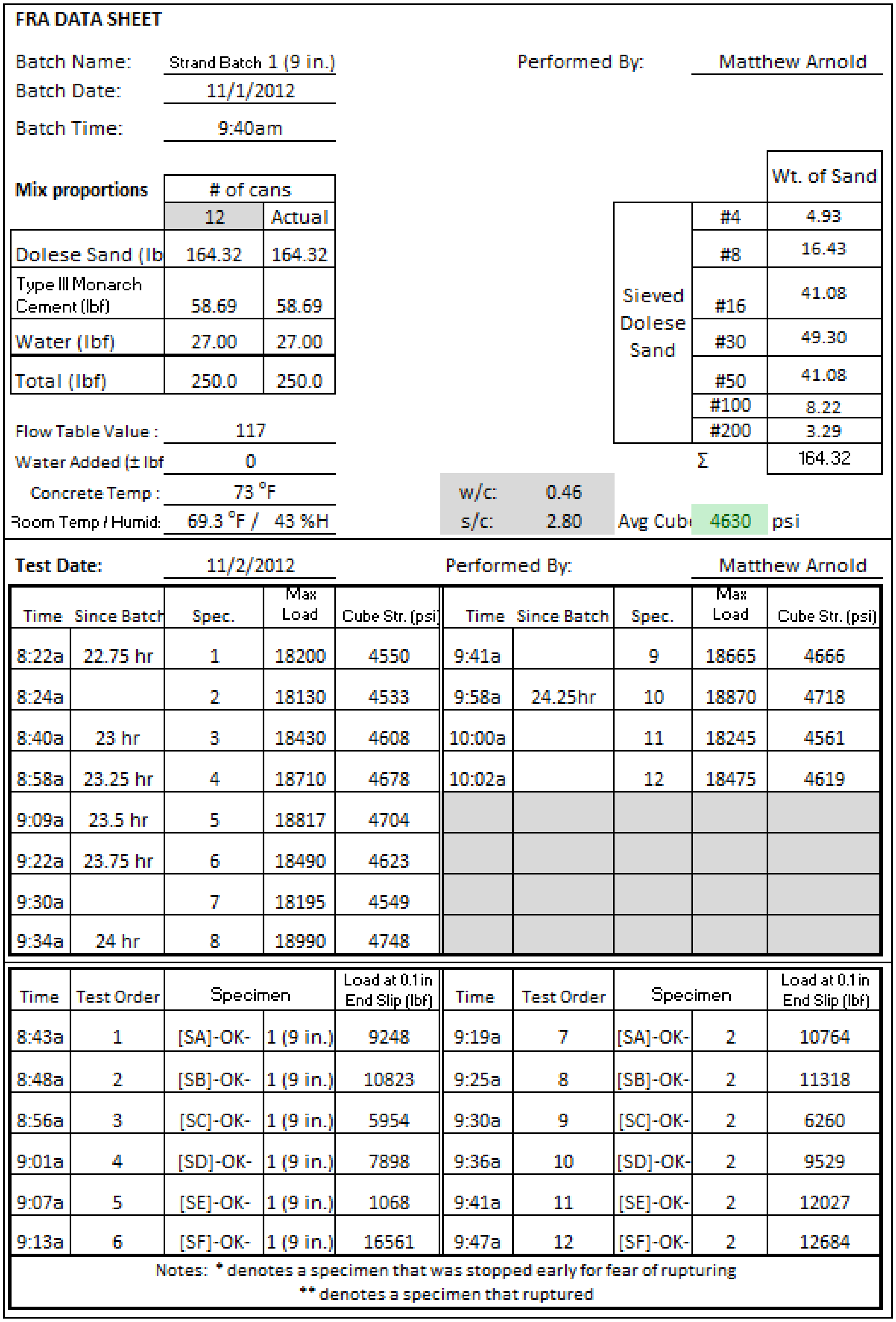
Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
9:20a	22.5 hr	1	17505	4376	11:26a	24.75 hr	9	18775	4694
9:28a	22.75 hr	2	17610	4403	11:36a		10	19730	4933
9:56a	23 hr	3	17925	4481	11:50a	25 hr	11	18460	4615
10:22a	23.5 hr	4	18195	4549	11:52a		12	17940	4485
10:24a		5	18325	4581					
10:48a	24 hr	6	18340	4585					
11:04a	24.25 hr	7	18700	4675					
11:16a	24.5 hr	8	18315	4579					

Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)	Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)
10:45a	3	[SA]-OK-	6	17143	10:53a	4	[SA]-OK-	6clean	14891
11:00a	5	[SB]-OK-	6	15962	11:06a	6	[SB]-OK-	6clean	19492
11:14a	7	[SC]-OK-	6	10776	11:20a	8	[SC]-OK-	6clean	8468
11:24a	9	[SD]-OK-	6	13261	11:30a	10	[SD]-OK-	6clean	11623
11:35a	11	[SE]-OK-	6	20818 *	11:42a	12	[SE]-OK-	6clean	20819 *
10:29a	1	[SF]-OK-	6	18100 *	10:36a	2	[SF]-OK-	6clean	17316

Notes: * denotes a specimen that was stopped early for fear of rupturing

** denotes a specimen that ruptured

Figure J.6 As-received and cleaned strands, batch summary #6 (16 in. bond length)



FRA DATA SHEET

Batch Name: Strand Batch 1 (9 in.)
Performed By: Matthew Arnold
Batch Date: 11/1/2012
Batch Time: 9:40am

Mix proportions	# of cans	
	12	Actual
Dolese Sand (lb	164.32	164.32
Type III Monarch Cement (lbf)	58.69	58.69
Water (lbf)	27.00	27.00
Total (lbf)	250.0	250.0

		Wt. of Sand
Sieved Dolese Sand	#4	4.93
	#8	16.43
	#16	41.08
	#30	49.30
	#50	41.08
	#100	8.22
	#200	3.29
	Σ	164.32

Flow Table Value : 117
Water Added (± lbf 0
Concrete Temp : 73 °F
Room Temp / Humid: 69.3 °F / 43 %H

w/c: 0.46
s/c: 2.80
Avg Cub 4630 psi

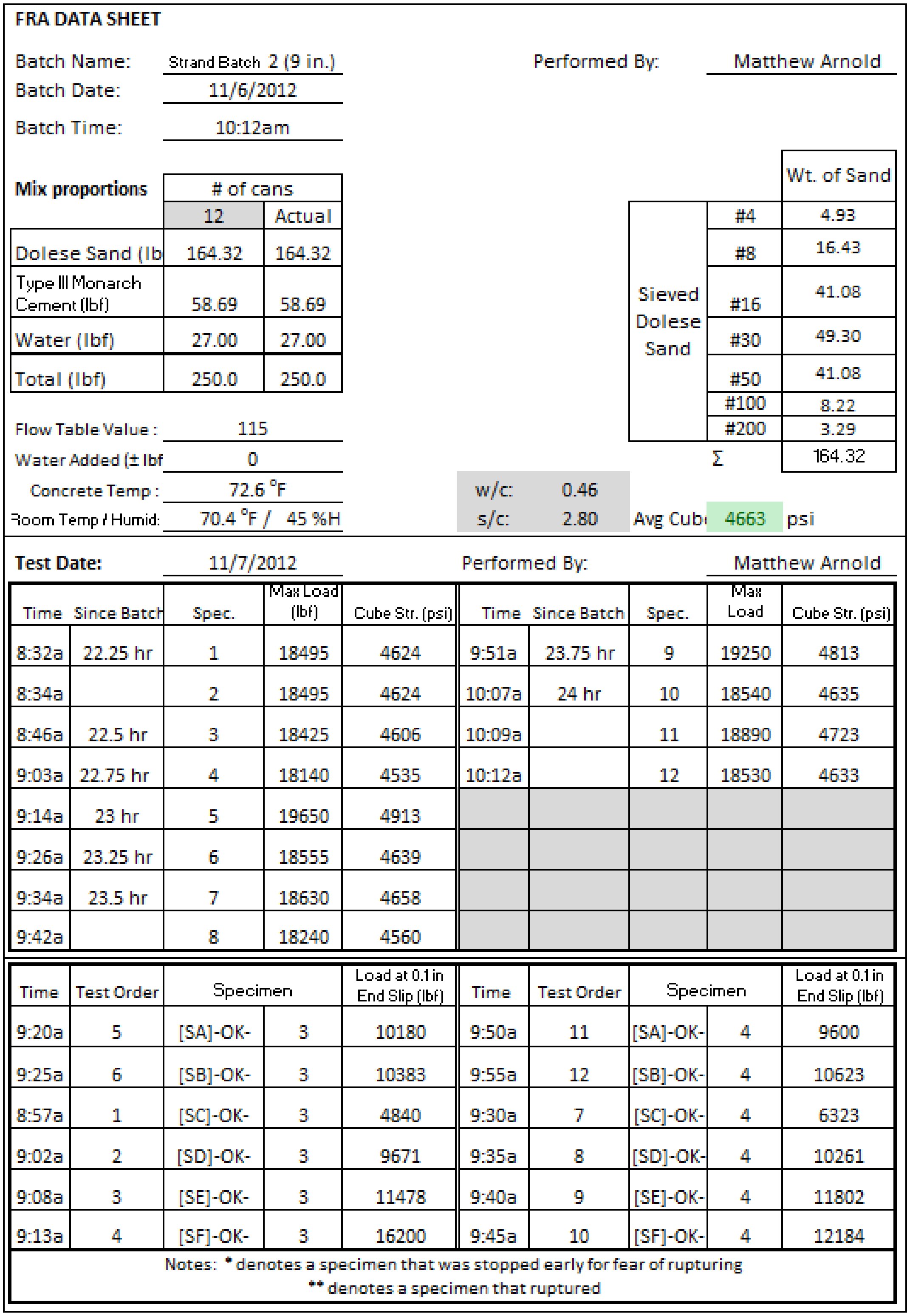
Test Date: 11/2/2012
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:22a	22.75 hr	1	18200	4550	9:41a		9	18665	4666
8:24a		2	18130	4533	9:58a	24.25hr	10	18870	4718
8:40a	23 hr	3	18430	4608	10:00a		11	18245	4561
8:58a	23.25 hr	4	18710	4678	10:02a		12	18475	4619
9:09a	23.5 hr	5	18817	4704					
9:22a	23.75 hr	6	18490	4623					
9:30a		7	18195	4549					
9:34a	24 hr	8	18990	4748					

Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)	Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)
8:43a	1	[SA]-OK-	1 (9 in.)	9248	9:19a	7	[SA]-OK-	2	10764
8:48a	2	[SB]-OK-	1 (9 in.)	10823	9:25a	8	[SB]-OK-	2	11318
8:56a	3	[SC]-OK-	1 (9 in.)	5954	9:30a	9	[SC]-OK-	2	6260
9:01a	4	[SD]-OK-	1 (9 in.)	7898	9:36a	10	[SD]-OK-	2	9529
9:07a	5	[SE]-OK-	1 (9 in.)	1068	9:41a	11	[SE]-OK-	2	12027
9:13a	6	[SF]-OK-	1 (9 in.)	16561	9:47a	12	[SF]-OK-	2	12684

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure J.7 As-received and cleaned strands, batch summary #1 (9 in. bond length)



FRA DATA SHEET

Batch Name: Strand Batch 2 (9 in.)

Performed By: Matthew Arnold

Batch Date: 11/6/2012

Batch Time: 10:12am

Mix proportions	# of cans	
	12	Actual
Dolese Sand (Ib	164.32	164.32
Type III Monarch Cement (lbf)	58.69	58.69
Water (lbf)	27.00	27.00
Total (lbf)	250.0	250.0

		Wt. of Sand
Sieved Dolese Sand	#4	4.93
	#8	16.43
	#16	41.08
	#30	49.30
	#50	41.08
	#100	8.22
	#200	3.29
	Σ	164.32

Flow Table Value : 115

Water Added (± lbf 0

Concrete Temp : 72.6 °F

Room Temp / Humid: 70.4 °F / 45 %H

w/c: 0.46

s/c: 2.80

Avg Cub 4663 psi

Test Date: 11/7/2012

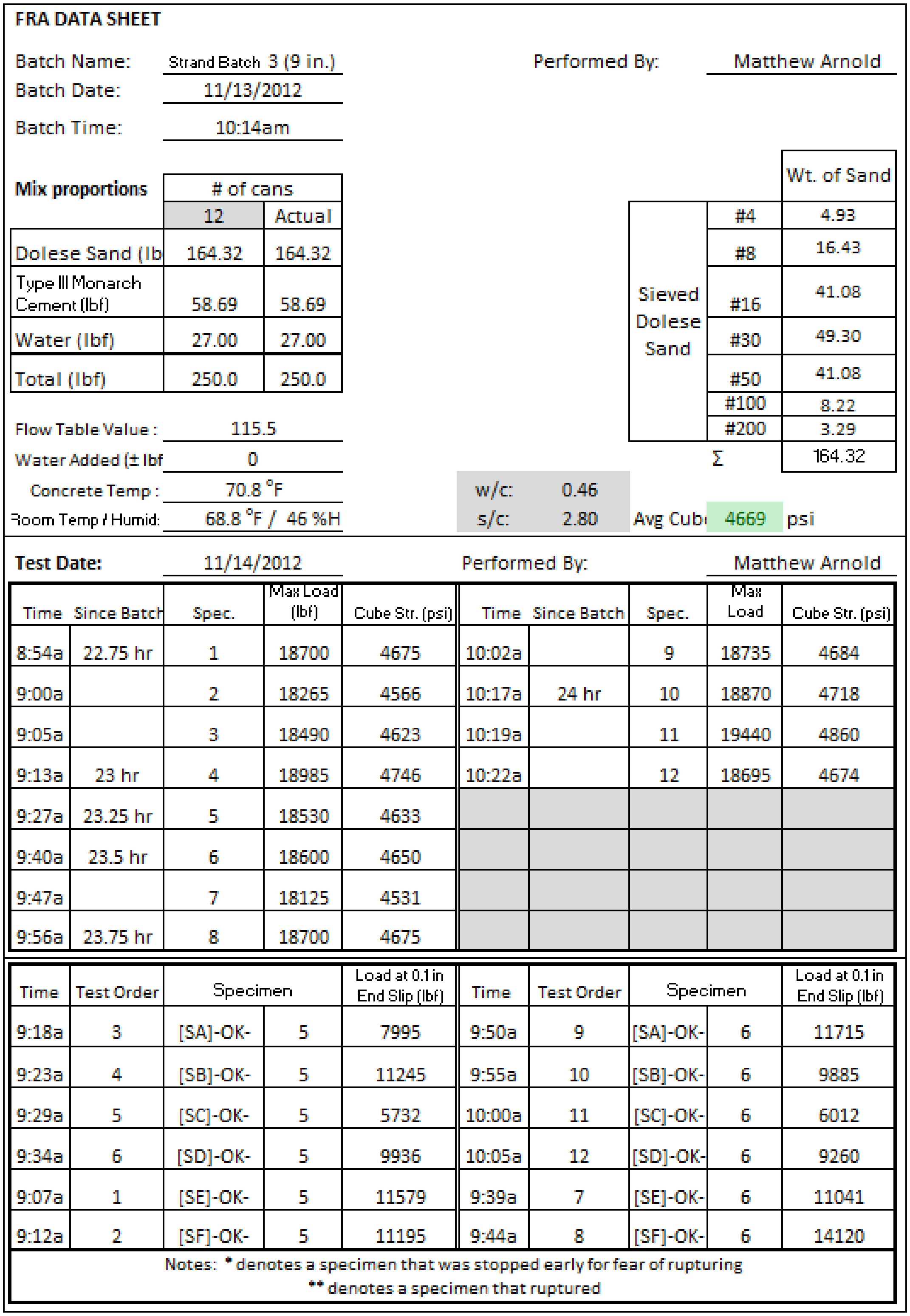
Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:32a	22.25 hr	1	18495	4624	9:51a	23.75 hr	9	19250	4813
8:34a		2	18495	4624	10:07a	24 hr	10	18540	4635
8:46a	22.5 hr	3	18425	4606	10:09a		11	18890	4723
9:03a	22.75 hr	4	18140	4535	10:12a		12	18530	4633
9:14a	23 hr	5	19650	4913					
9:26a	23.25 hr	6	18555	4639					
9:34a	23.5 hr	7	18630	4658					
9:42a		8	18240	4560					

Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)	Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)
9:20a	5	[SA]-OK-	3	10180	9:50a	11	[SA]-OK-	4	9600
9:25a	6	[SB]-OK-	3	10383	9:55a	12	[SB]-OK-	4	10623
8:57a	1	[SC]-OK-	3	4840	9:30a	7	[SC]-OK-	4	6323
9:02a	2	[SD]-OK-	3	9671	9:35a	8	[SD]-OK-	4	10261
9:08a	3	[SE]-OK-	3	11478	9:40a	9	[SE]-OK-	4	11802
9:13a	4	[SF]-OK-	3	16200	9:45a	10	[SF]-OK-	4	12184

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure J.8 As-received and cleaned strands, batch summary #2 (9 in. bond length)



FRA DATA SHEET

Batch Name: Strand Batch 3 (9 in.) Performed By: Matthew Arnold
Batch Date: 11/13/2012
Batch Time: 10:14am

Mix proportions	# of cans	
	12	Actual
Dolese Sand (lb	164.32	164.32
Type III Monarch Cement (lbf)	58.69	58.69
Water (lbf)	27.00	27.00
Total (lbf)	250.0	250.0

		Wt. of Sand
Sieved Dolese Sand	#4	4.93
	#8	16.43
	#16	41.08
	#30	49.30
	#50	41.08
	#100	8.22
	#200	3.29
	Σ	164.32

Flow Table Value : 115.5
Water Added (± lbf 0
Concrete Temp : 70.8 °F
Room Temp / Humid: 68.8 °F / 46 %H

w/c: 0.46
s/c: 2.80
Avg Cub 4669 psi

Test Date: 11/14/2012 Performed By: Matthew Arnold

Time	Since Batch	Spec.	Max Load (lbf)	Cube Str. (psi)	Time	Since Batch	Spec.	Max Load	Cube Str. (psi)
8:54a	22.75 hr	1	18700	4675	10:02a		9	18735	4684
9:00a		2	18265	4566	10:17a	24 hr	10	18870	4718
9:05a		3	18490	4623	10:19a		11	19440	4860
9:13a	23 hr	4	18985	4746	10:22a		12	18695	4674
9:27a	23.25 hr	5	18530	4633					
9:40a	23.5 hr	6	18600	4650					
9:47a		7	18125	4531					
9:56a	23.75 hr	8	18700	4675					

Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)	Time	Test Order	Specimen		Load at 0.1 in End Slip (lbf)
9:18a	3	[SA]-OK-	5	7995	9:50a	9	[SA]-OK-	6	11715
9:23a	4	[SB]-OK-	5	11245	9:55a	10	[SB]-OK-	6	9885
9:29a	5	[SC]-OK-	5	5732	10:00a	11	[SC]-OK-	6	6012
9:34a	6	[SD]-OK-	5	9936	10:05a	12	[SD]-OK-	6	9260
9:07a	1	[SE]-OK-	5	11579	9:39a	7	[SE]-OK-	6	11041
9:12a	2	[SF]-OK-	5	11195	9:44a	8	[SF]-OK-	6	14120

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure J.9 As-received and cleaned strands, batch summary #3 (9 in. bond length)

Appendix K - Lab Phase, Strand; As-Received and Cleaned Individual Pullout Graphs

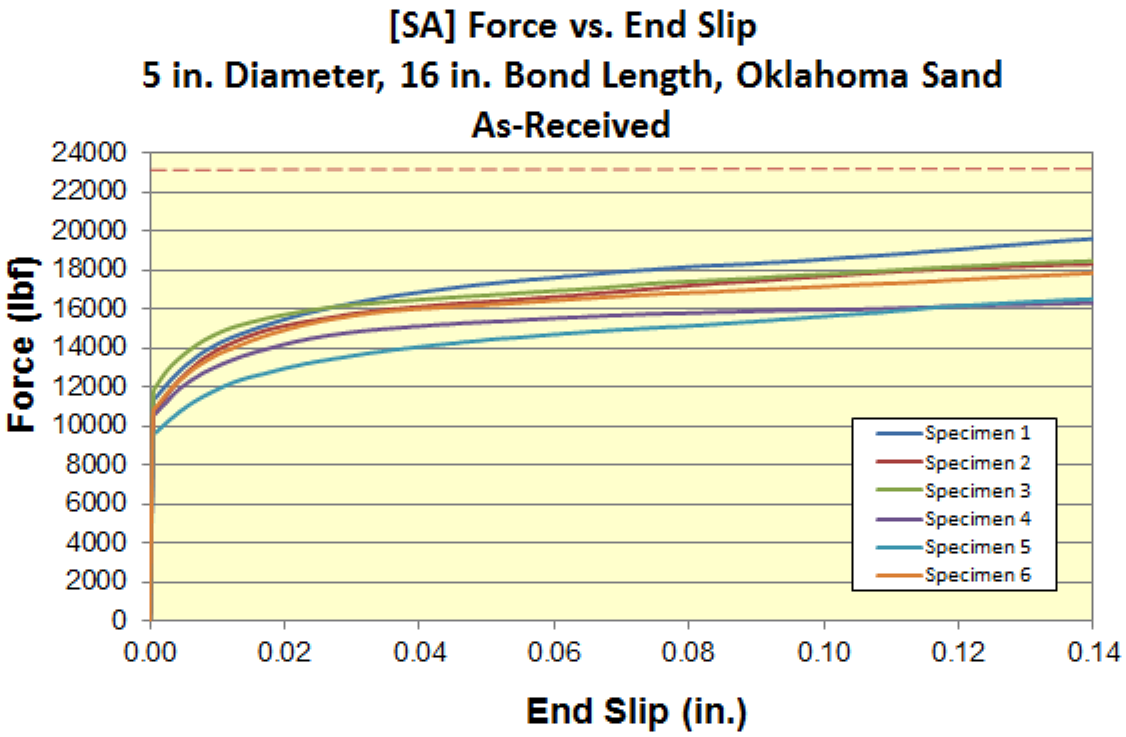


Figure K.1 As-received [SA] force vs. end slip individual graphs (16 in. bond length)

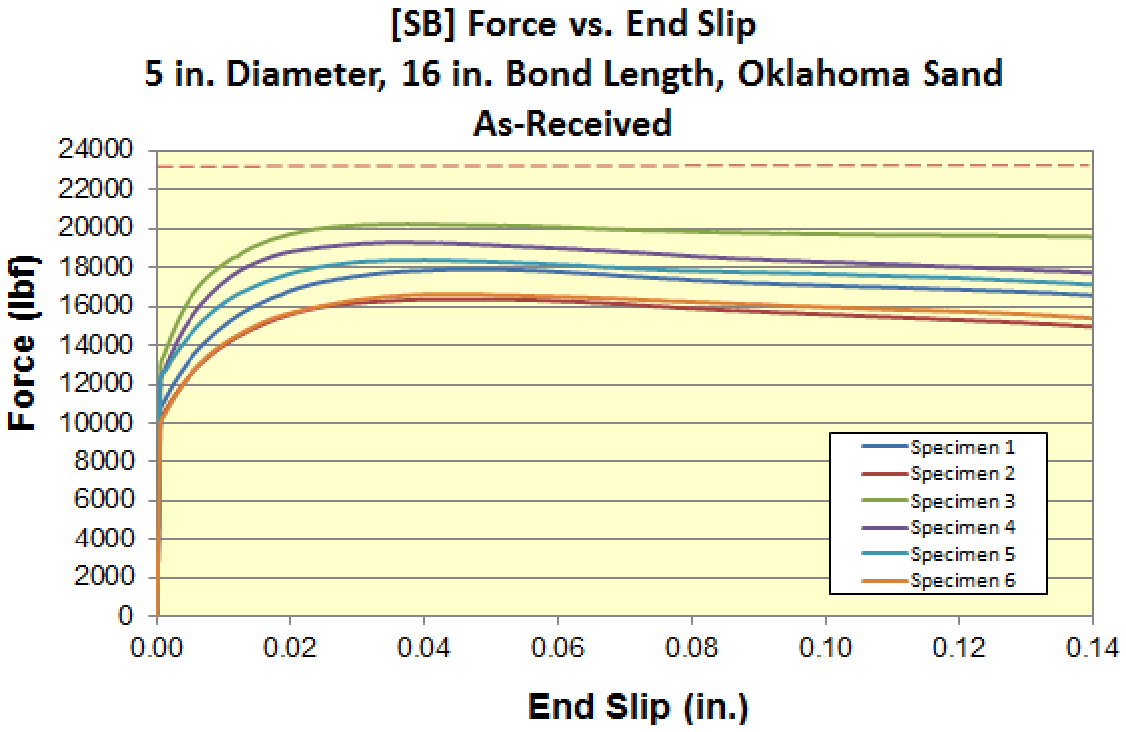


Figure K.2 As-received [SB] force vs. end slip individual graphs (16 in. bond length)

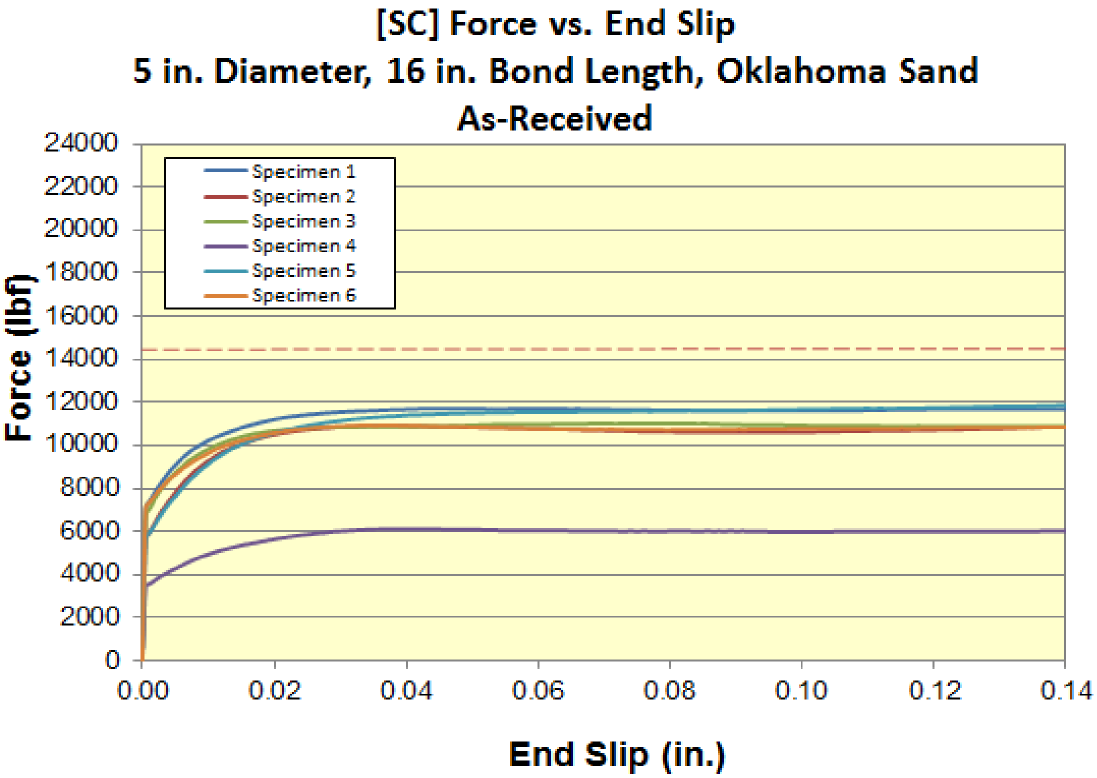


Figure K.3 As-received [SC] force vs. end slip individual graphs (16 in. bond length)

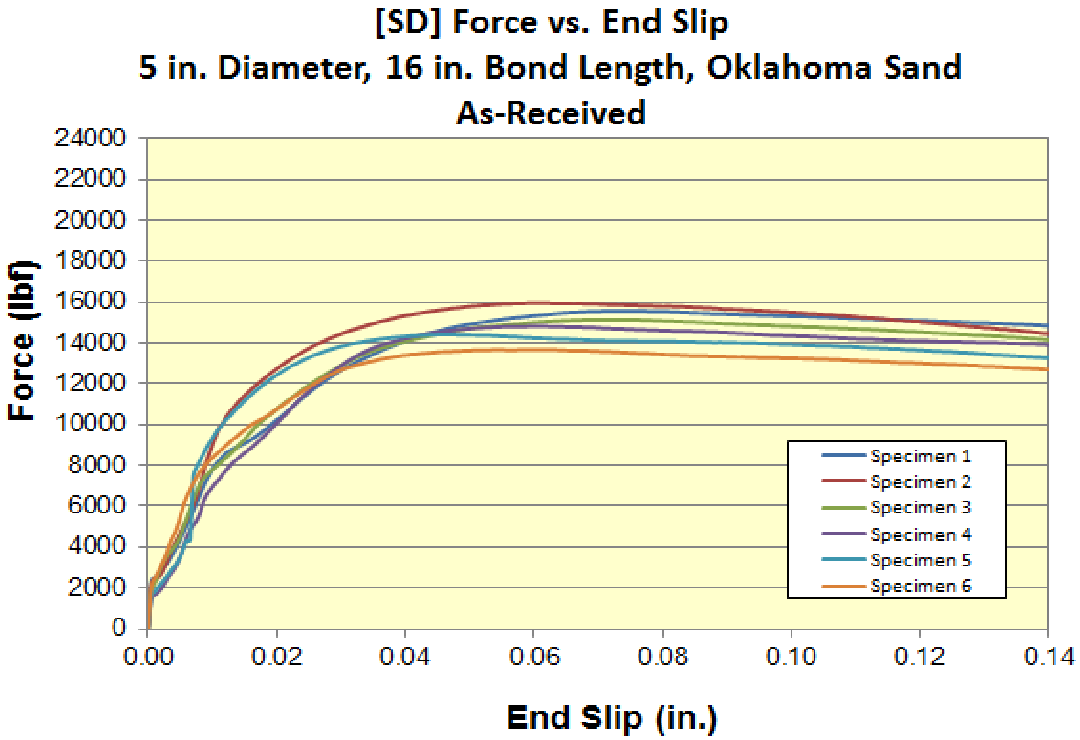


Figure K.4 As-received [SD] force vs. end slip individual graphs (16 in. bond length)

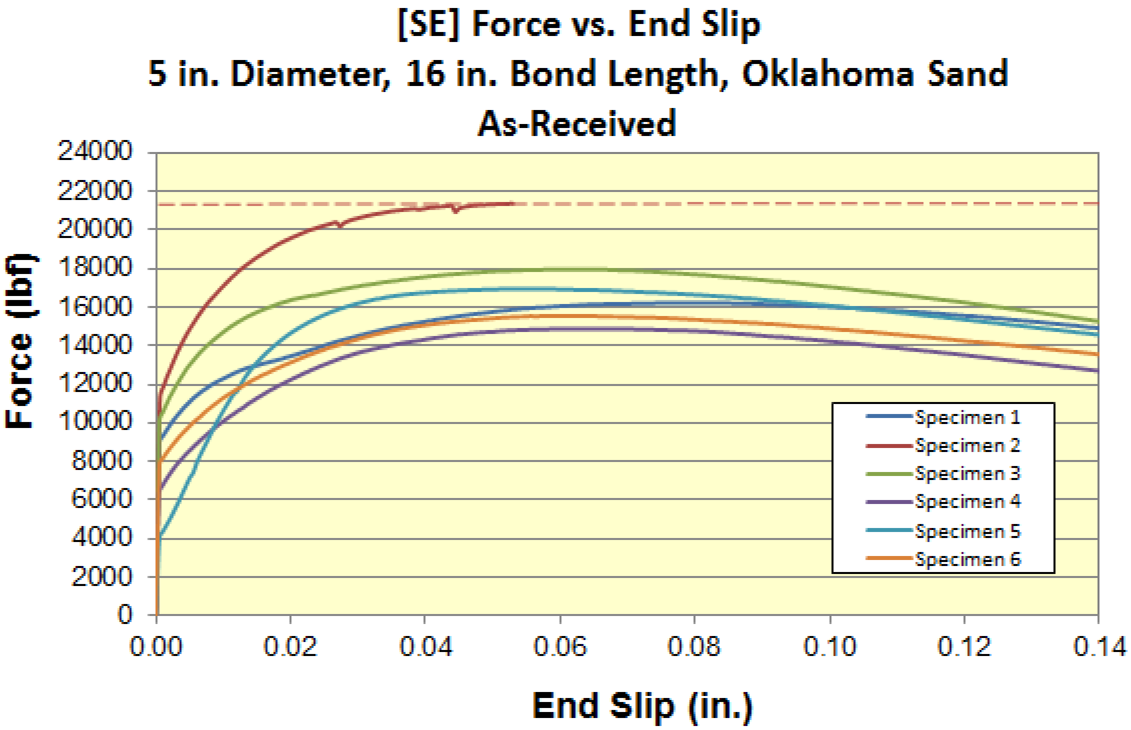


Figure K.5 As-received [SE] force vs. end slip individual graphs (16 in. bond length)

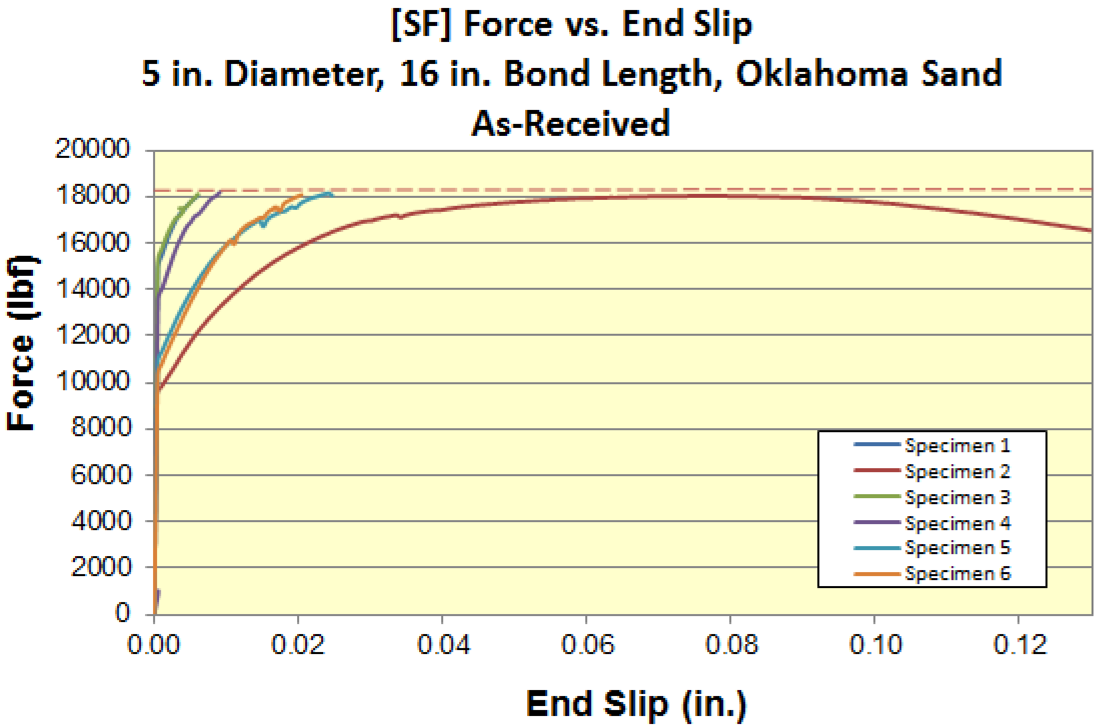


Figure K.6 As-received [SF] force vs. end slip individual graphs (16 in. bond length)

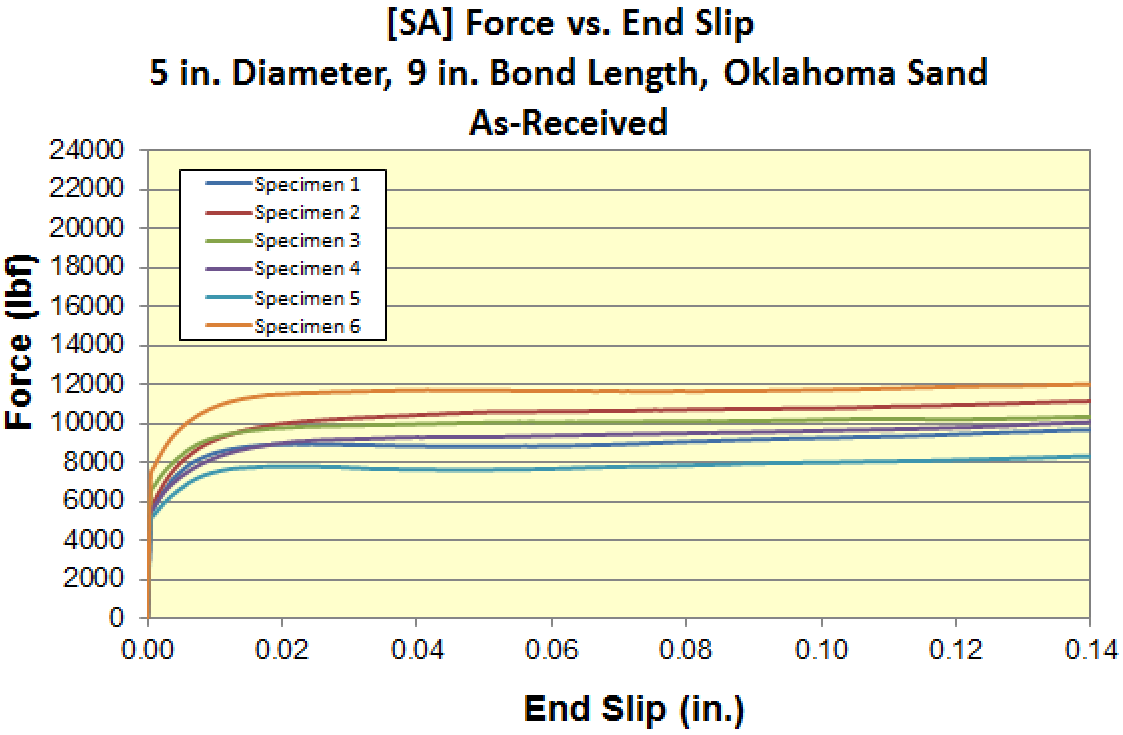


Figure K.7 As-received [SA] force vs. end slip individual graphs (9 in. bond length)

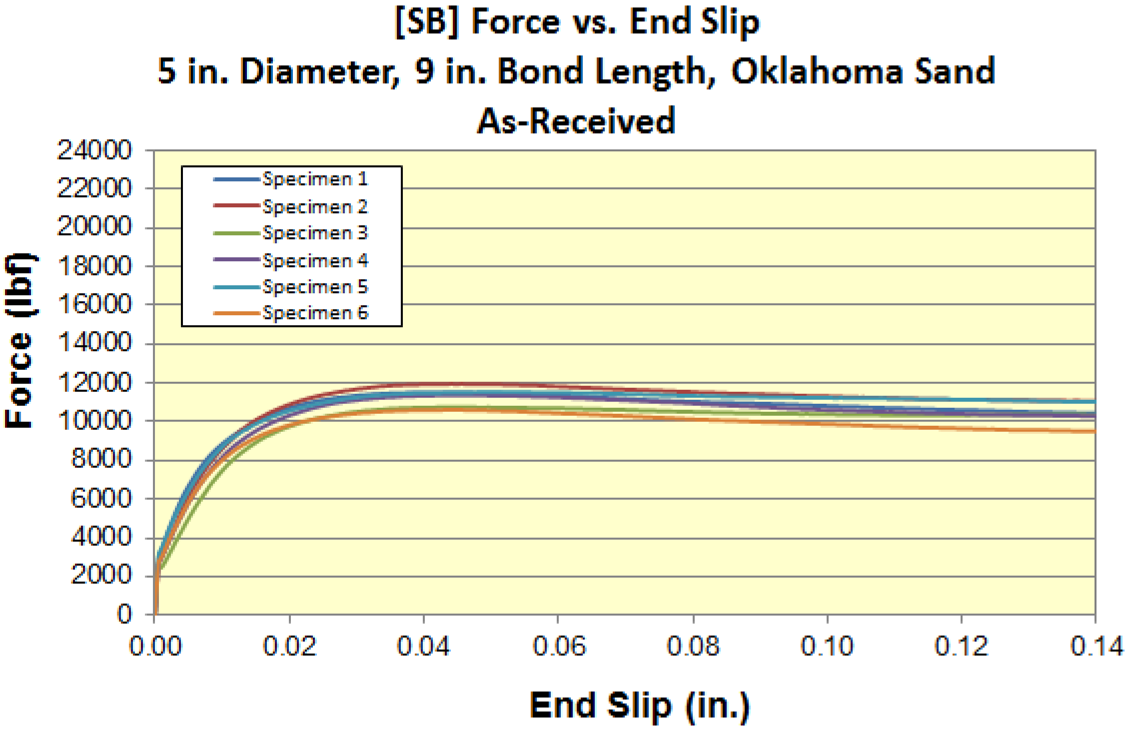


Figure K.8 As-received [SB] force vs. end slip individual graphs (9 in. bond length)

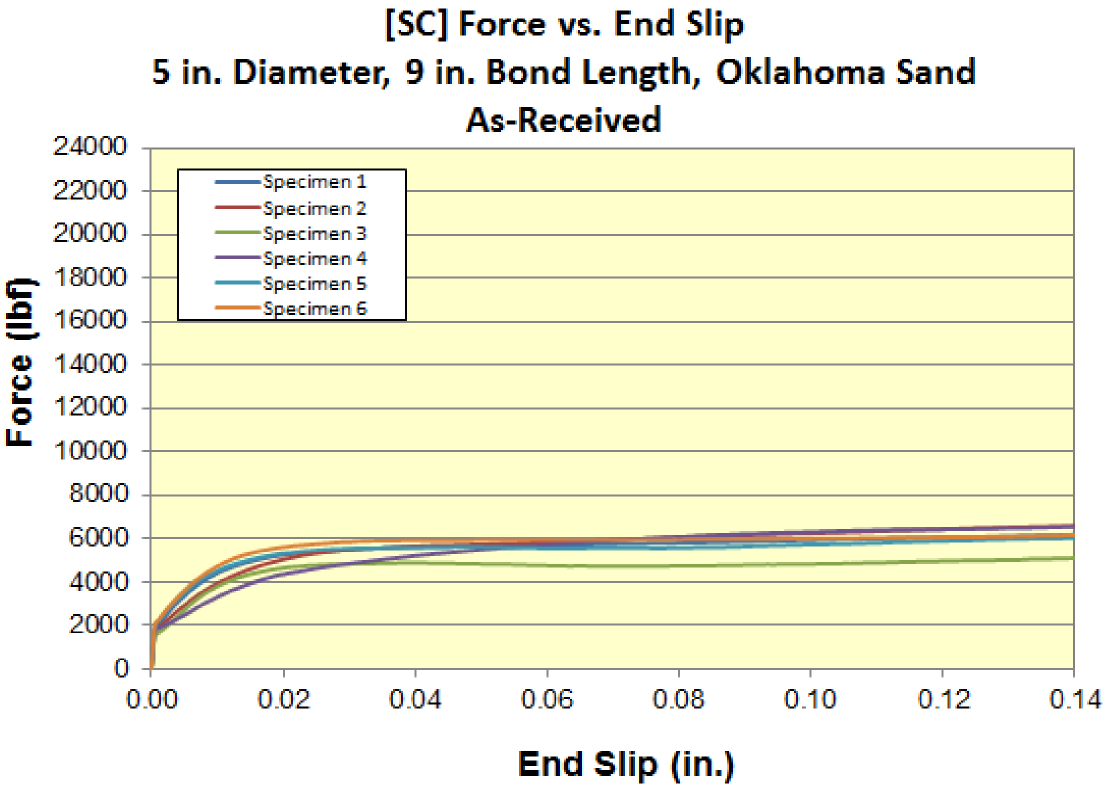


Figure K.9 As-received [SC] force vs. end slip individual graphs (9 in. bond length)

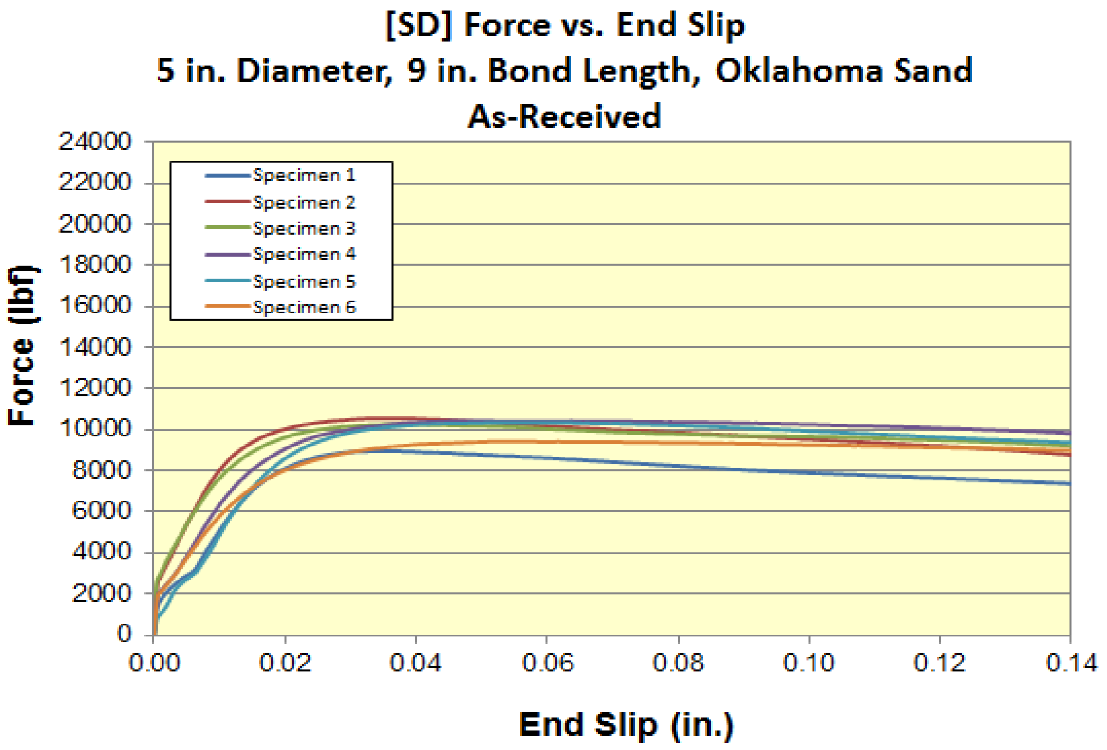


Figure K.10 As-received [SD] force vs. end slip individual graphs (9 in. bond length)

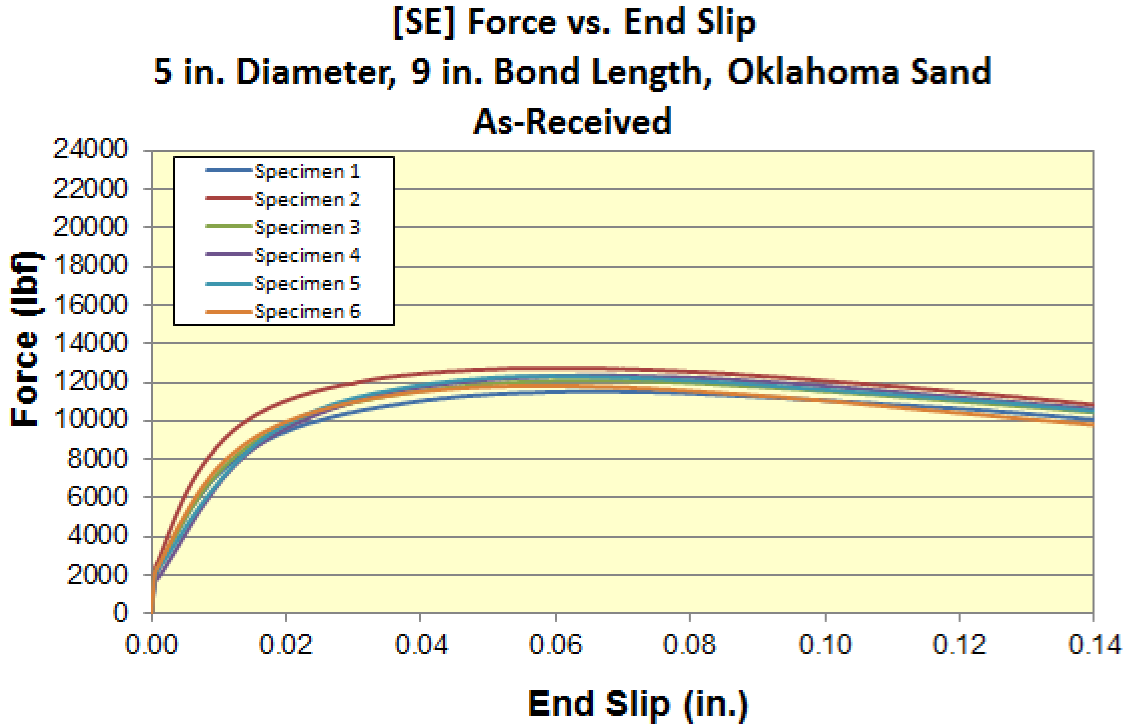


Figure K.11 As-received [SE] force vs. end slip individual graphs (9 in. bond length)

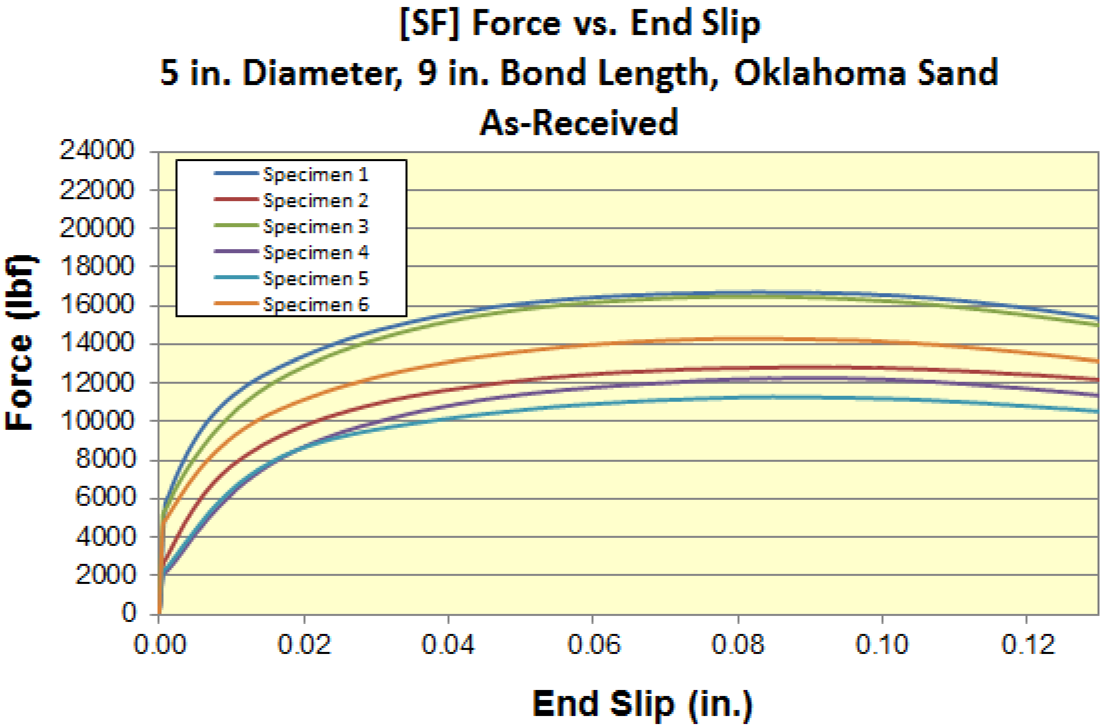


Figure K.12 As-received [SF] force vs. end slip individual graphs (9 in. bond length)

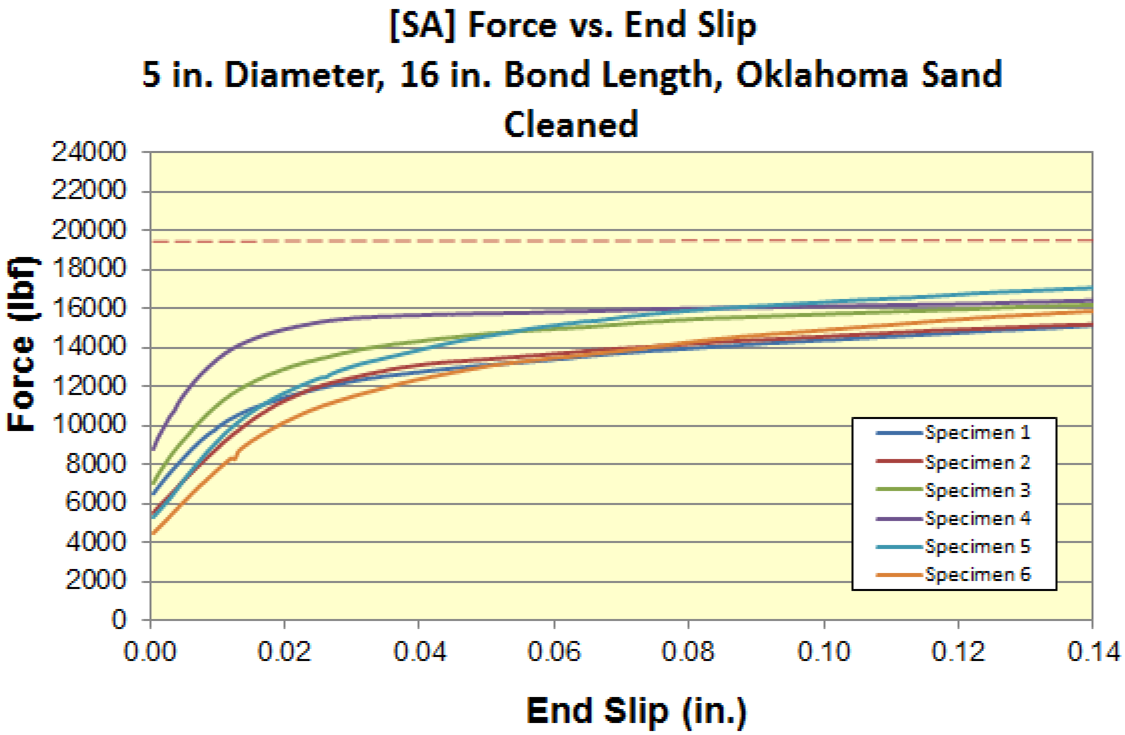


Figure K.13 Cleaned [SA] force vs. end slip individual graphs (16 in. bond length)

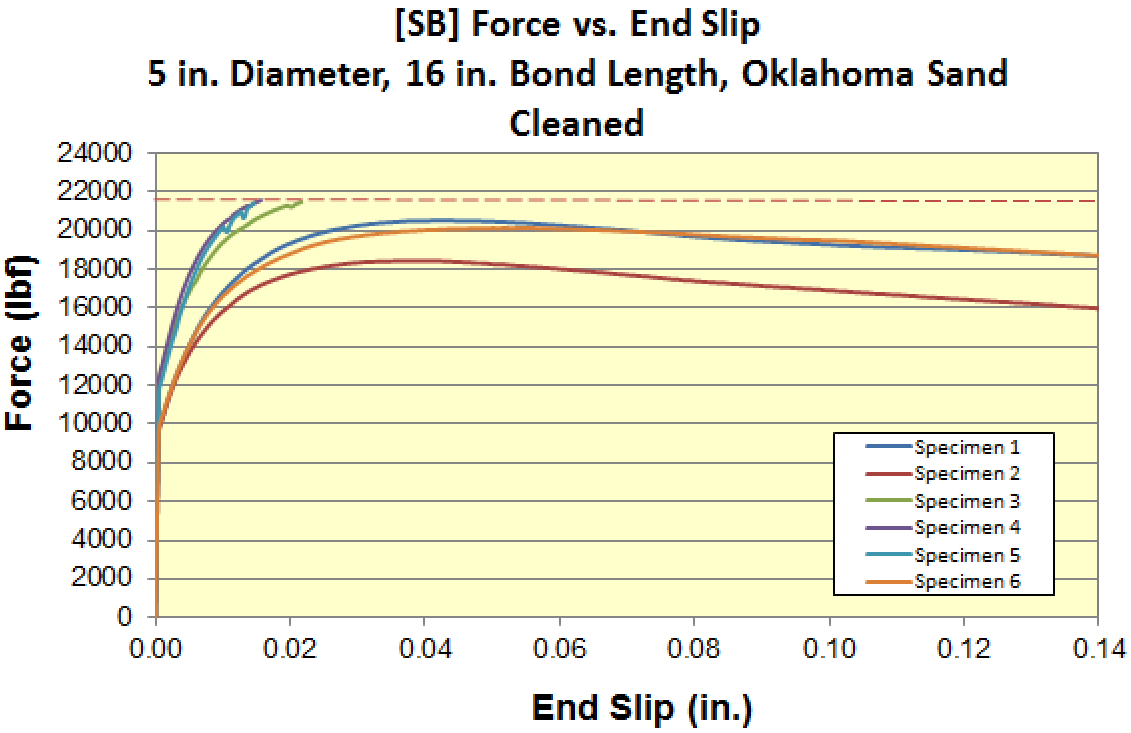


Figure K.14 Cleaned [SB] force vs. end slip individual graphs (16 in. bond length)

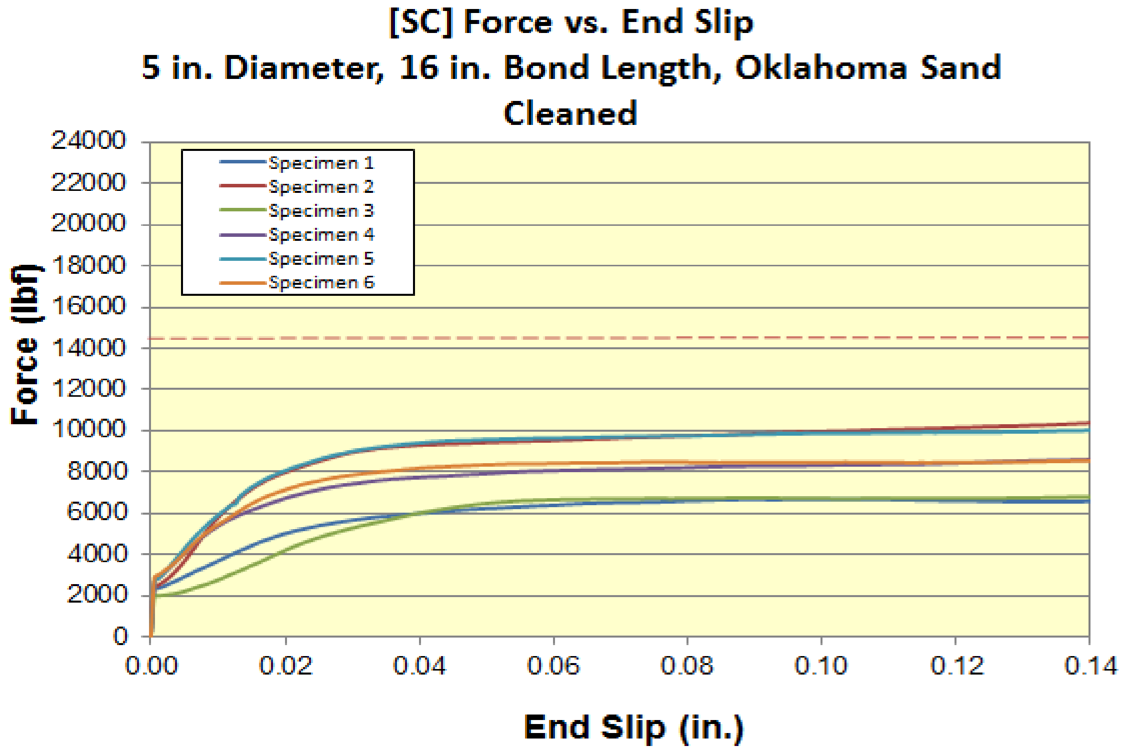


Figure K.15 Cleaned [SC] force vs. end slip individual graphs (16 in. bond length)

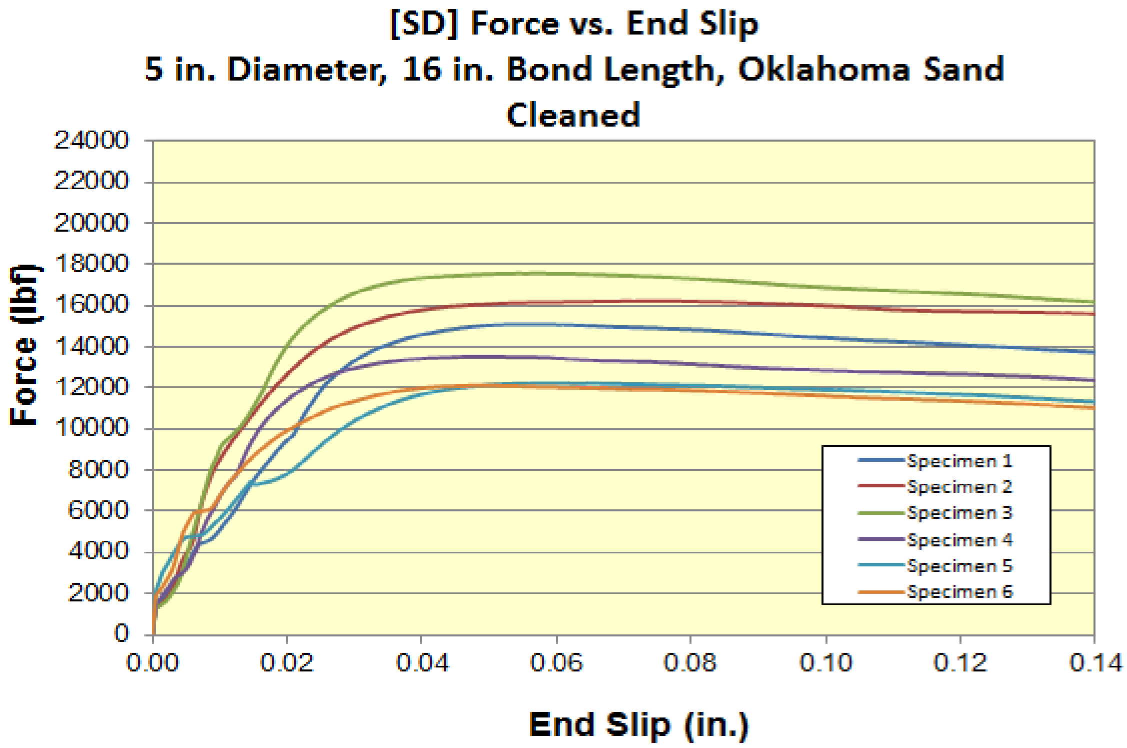


Figure K.16 Cleaned [SD] force vs. end slip individual graphs (16 in. bond length)

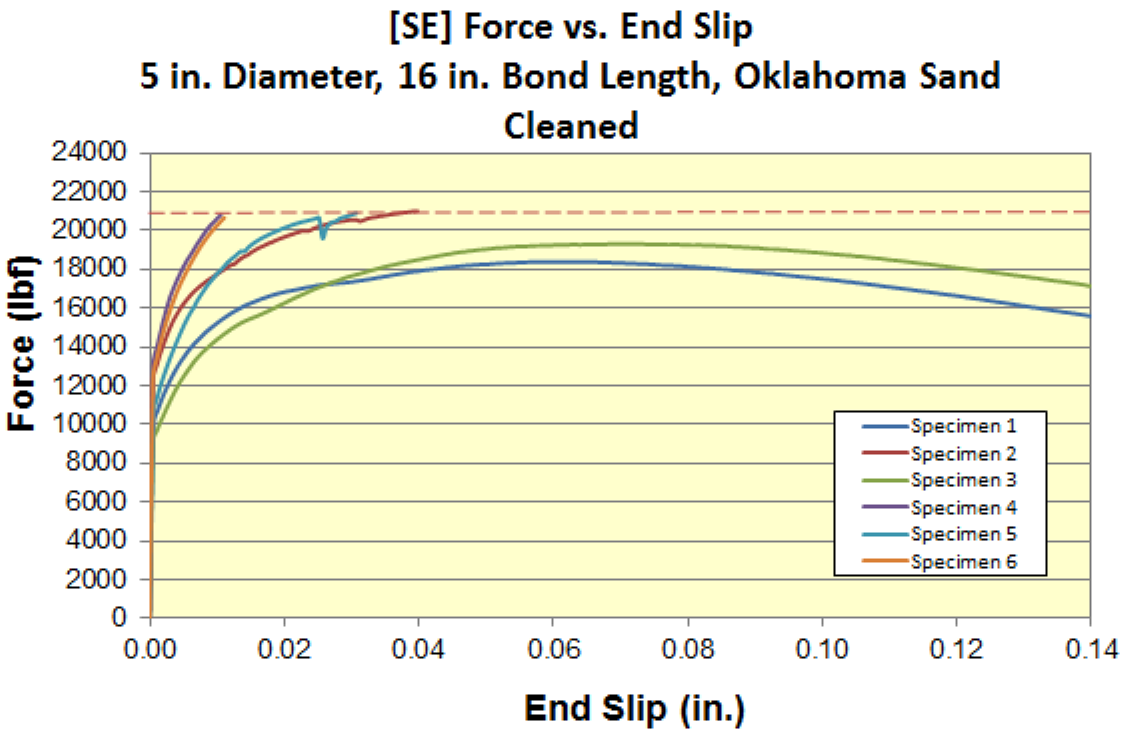


Figure K.17 Cleaned [SE] force vs. end slip individual graphs (16 in. bond length)

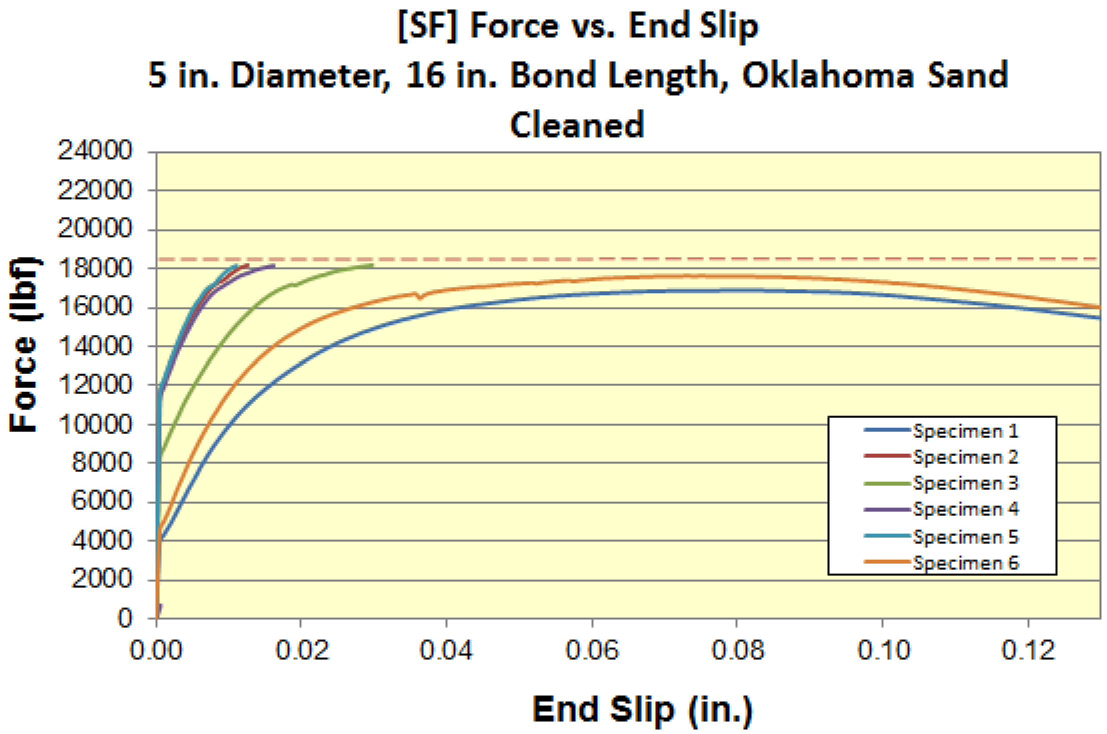


Figure K.18 Cleaned [SF] force vs. end slip individual graphs (16 in. bond length)

Appendix L - Lab Phase, Strand; As-Received vs. Cleaned Analysis

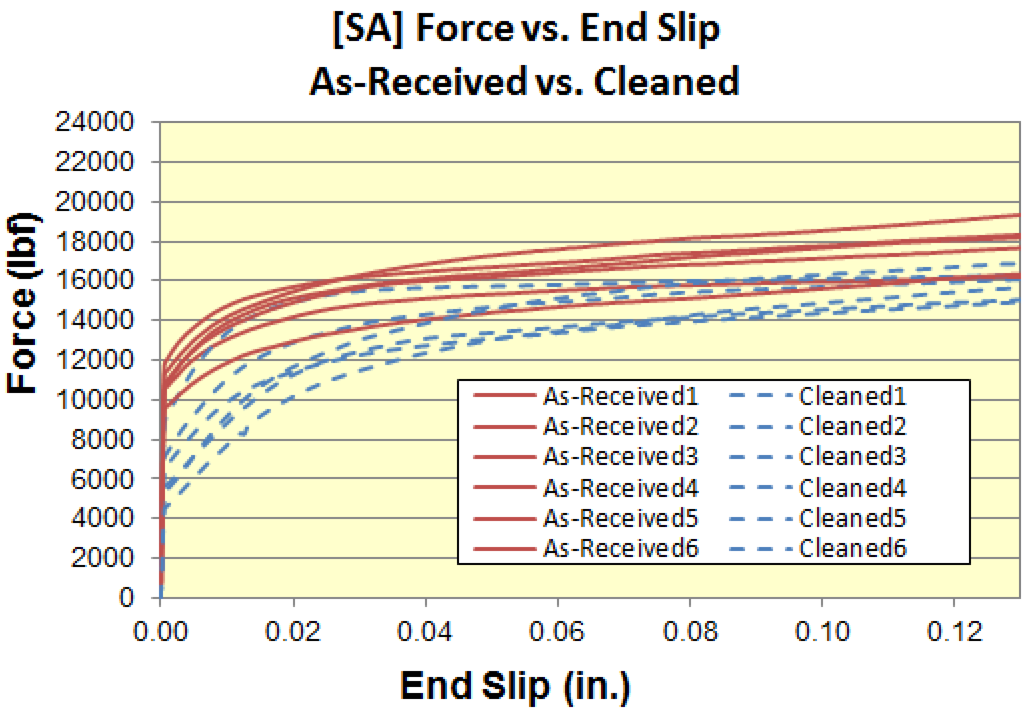


Figure L.1 [SA] force vs. end slip individual graphs, as-received vs. cleaned

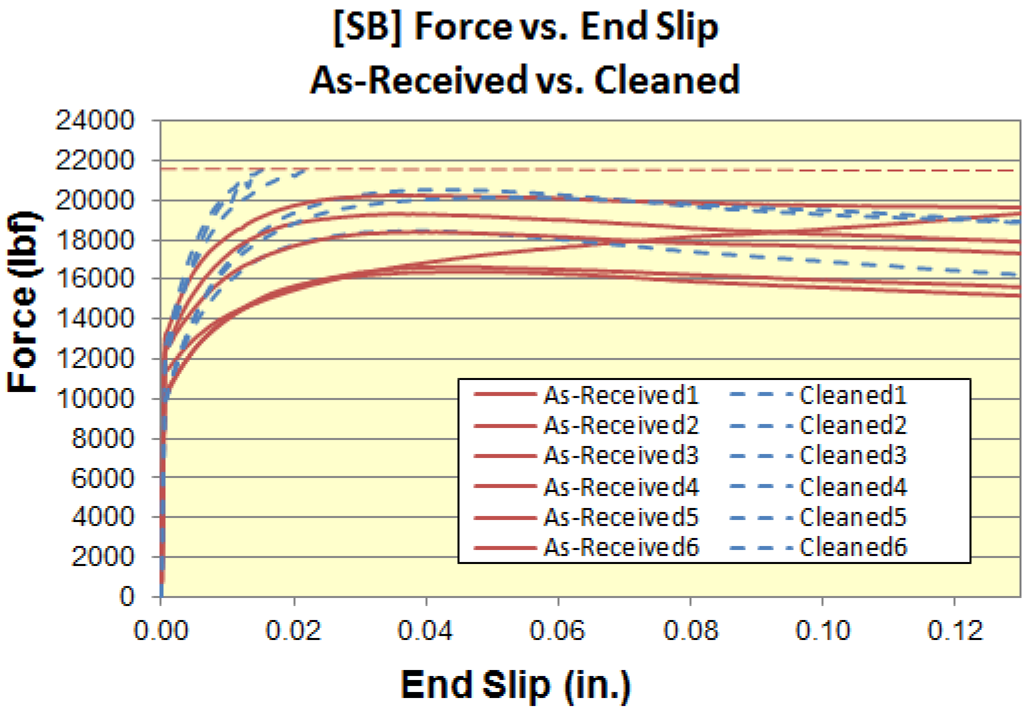


Figure L.2 [SB] force vs. end slip individual graphs, as-received vs. cleaned

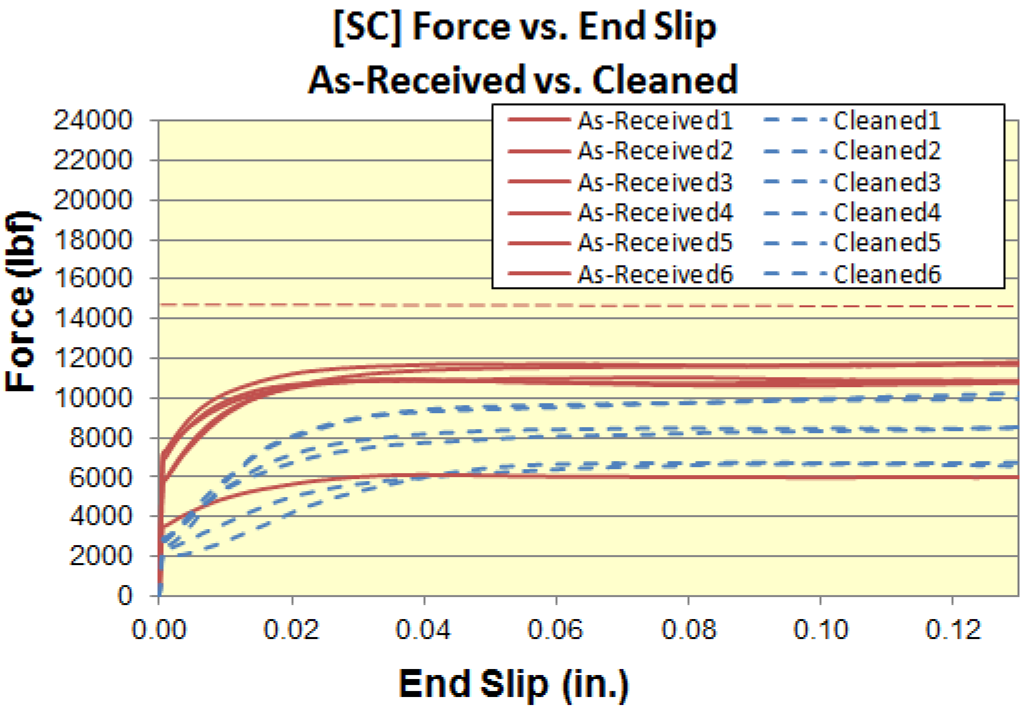


Figure L.3 [SC] force vs. end slip individual graphs, as-received vs. cleaned

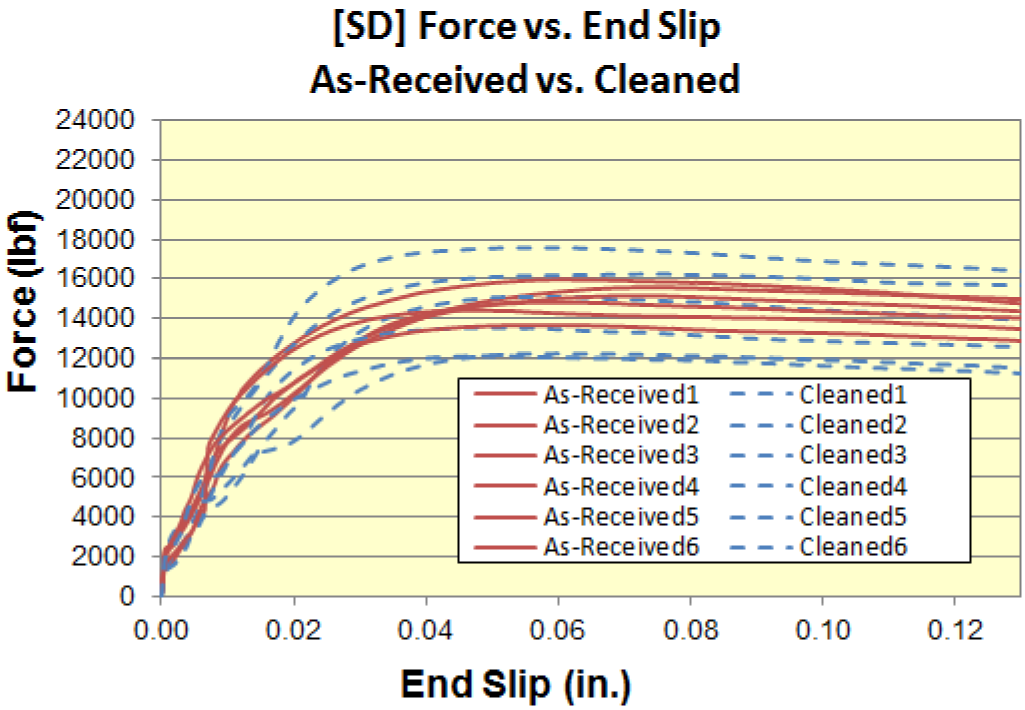


Figure L.4 [SD] force vs. end slip individual graphs, as-received vs. cleaned

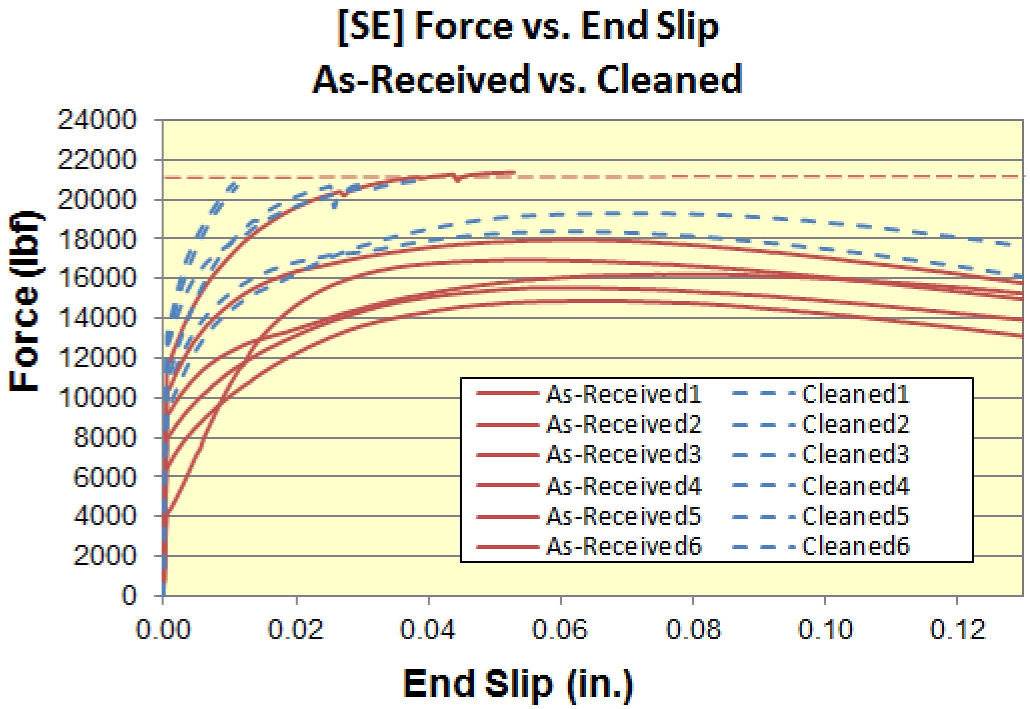


Figure L.5 [SE] force vs. end slip individual graphs, as-received vs. cleaned

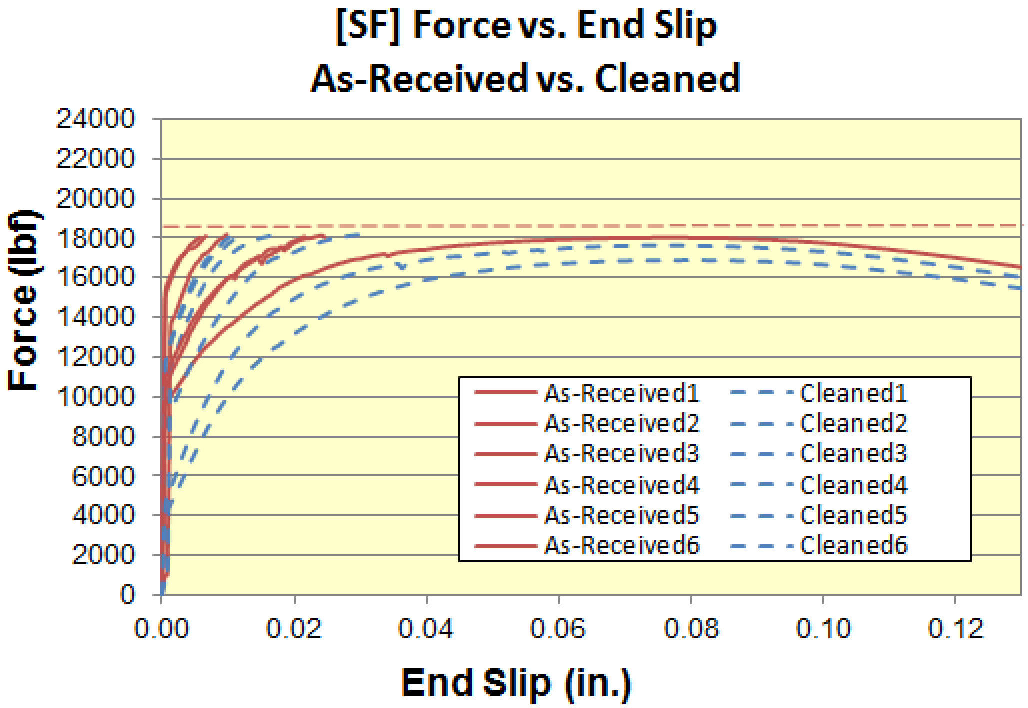
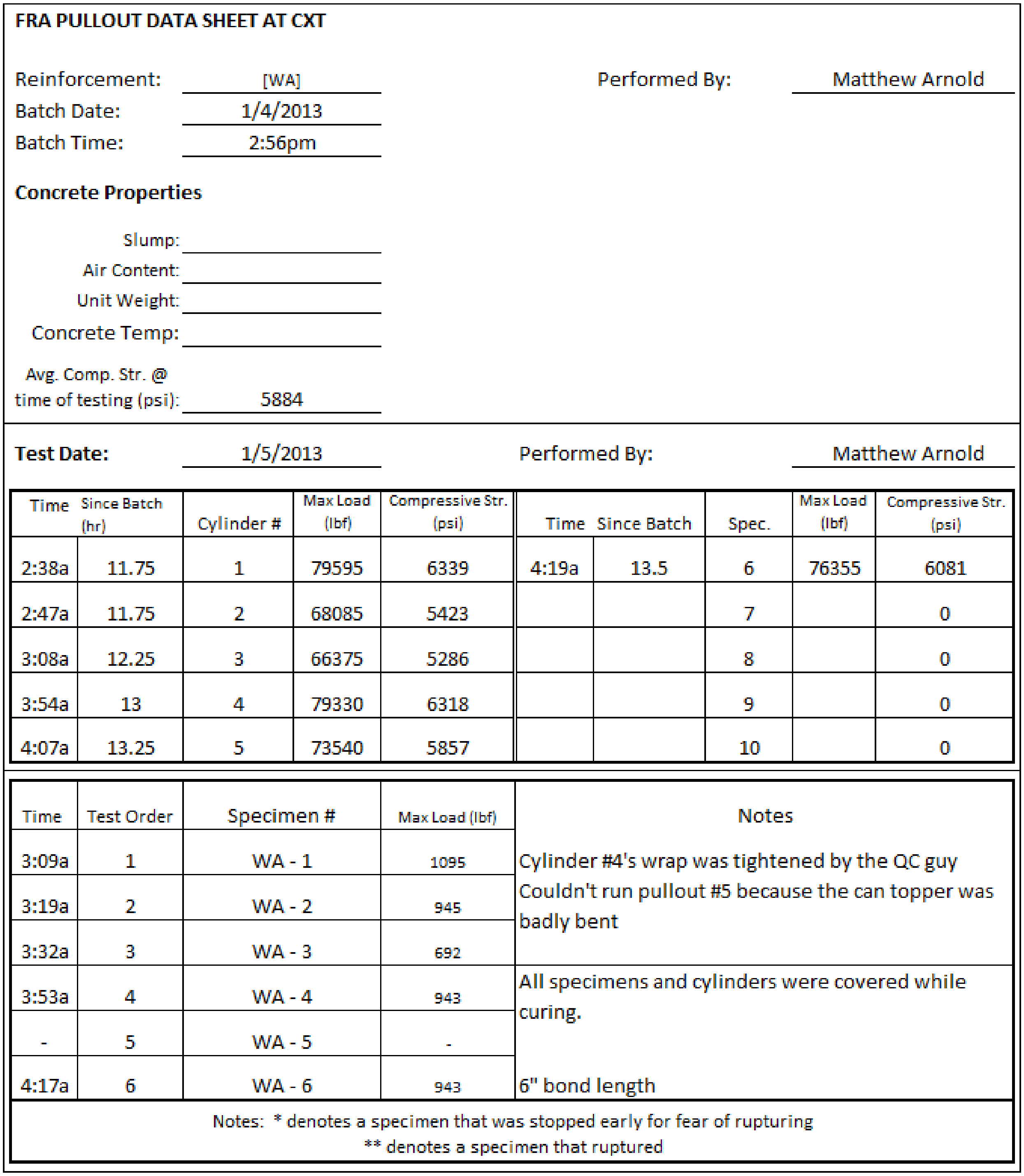


Figure L.6 [SF] force vs. end slip individual graphs, as-received vs. cleaned

Appendix M - Plant Phase, Wire and Strand; Batch Summaries



FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [WA]
Batch Date: 1/4/2013
Batch Time: 2:56pm
Performed By: Matthew Arnold

Concrete Properties

Slump:
Air Content:
Unit Weight:
Concrete Temp:
Avg. Comp. Str. @ time of testing (psi): 5884

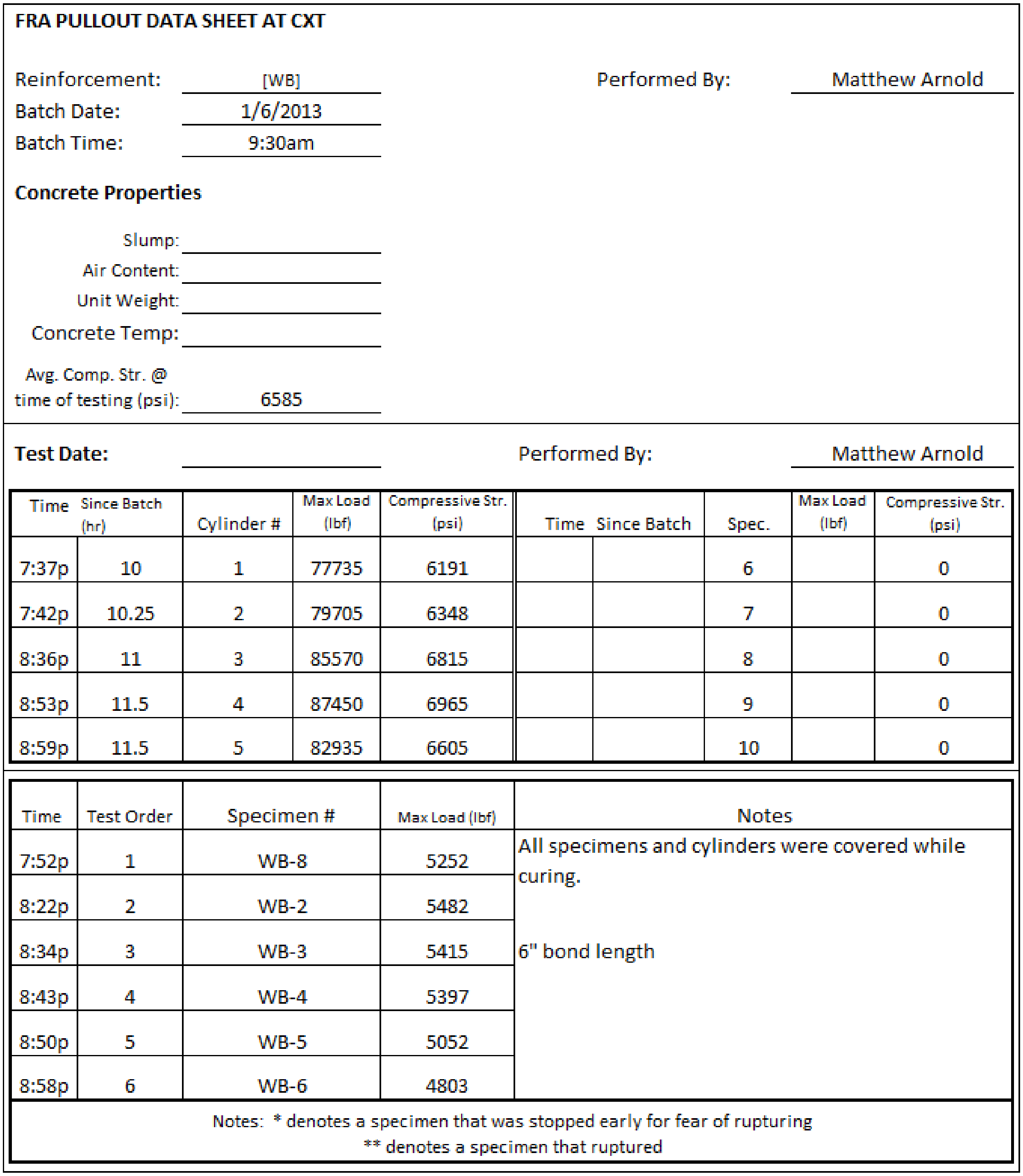
Test Date: 1/5/2013
Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
2:38a	11.75	1	79595	6339	4:19a	13.5	6	76355	6081
2:47a	11.75	2	68085	5423			7		0
3:08a	12.25	3	66375	5286			8		0
3:54a	13	4	79330	6318			9		0
4:07a	13.25	5	73540	5857			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
3:09a	1	WA - 1	1095	Cylinder #4's wrap was tightened by the QC guy Couldn't run pullout #5 because the can topper was badly bent
3:19a	2	WA - 2	945	
3:32a	3	WA - 3	692	
3:53a	4	WA - 4	943	All specimens and cylinders were covered while curing.
-	5	WA - 5	-	
4:17a	6	WA - 6	943	6" bond length

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M.1 As-received [WA] batch summary at CXT



FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [WB]
Batch Date: 1/6/2013
Batch Time: 9:30am

Performed By: Matthew Arnold

Concrete Properties

Slump:
Air Content:
Unit Weight:
Concrete Temp:
Avg. Comp. Str. @ time of testing (psi): 6585

Test Date:

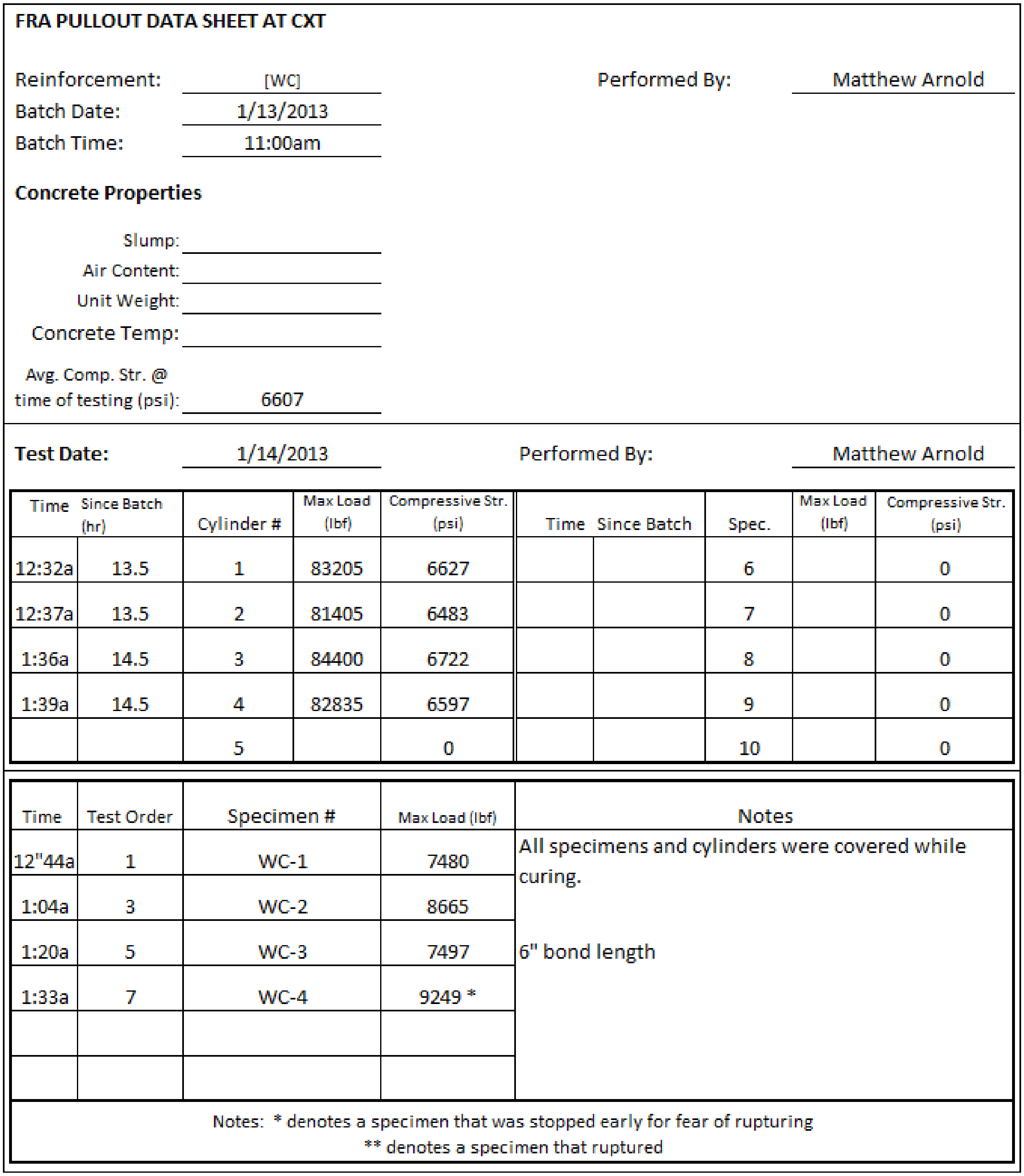
Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
7:37p	10	1	77735	6191			6		0
7:42p	10.25	2	79705	6348			7		0
8:36p	11	3	85570	6815			8		0
8:53p	11.5	4	87450	6965			9		0
8:59p	11.5	5	82935	6605			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
7:52p	1	WB-8	5252	All specimens and cylinders were covered while curing.
8:22p	2	WB-2	5482	
8:34p	3	WB-3	5415	6" bond length
8:43p	4	WB-4	5397	
8:50p	5	WB-5	5052	
8:58p	6	WB-6	4803	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M.2 As-received [WB] batch summary at CXT



FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [WC]
Batch Date: 1/13/2013
Batch Time: 11:00am

Performed By: Matthew Arnold

Concrete Properties

Slump:
Air Content:
Unit Weight:
Concrete Temp:
Avg. Comp. Str. @ time of testing (psi): 6607

Test Date: 1/14/2013

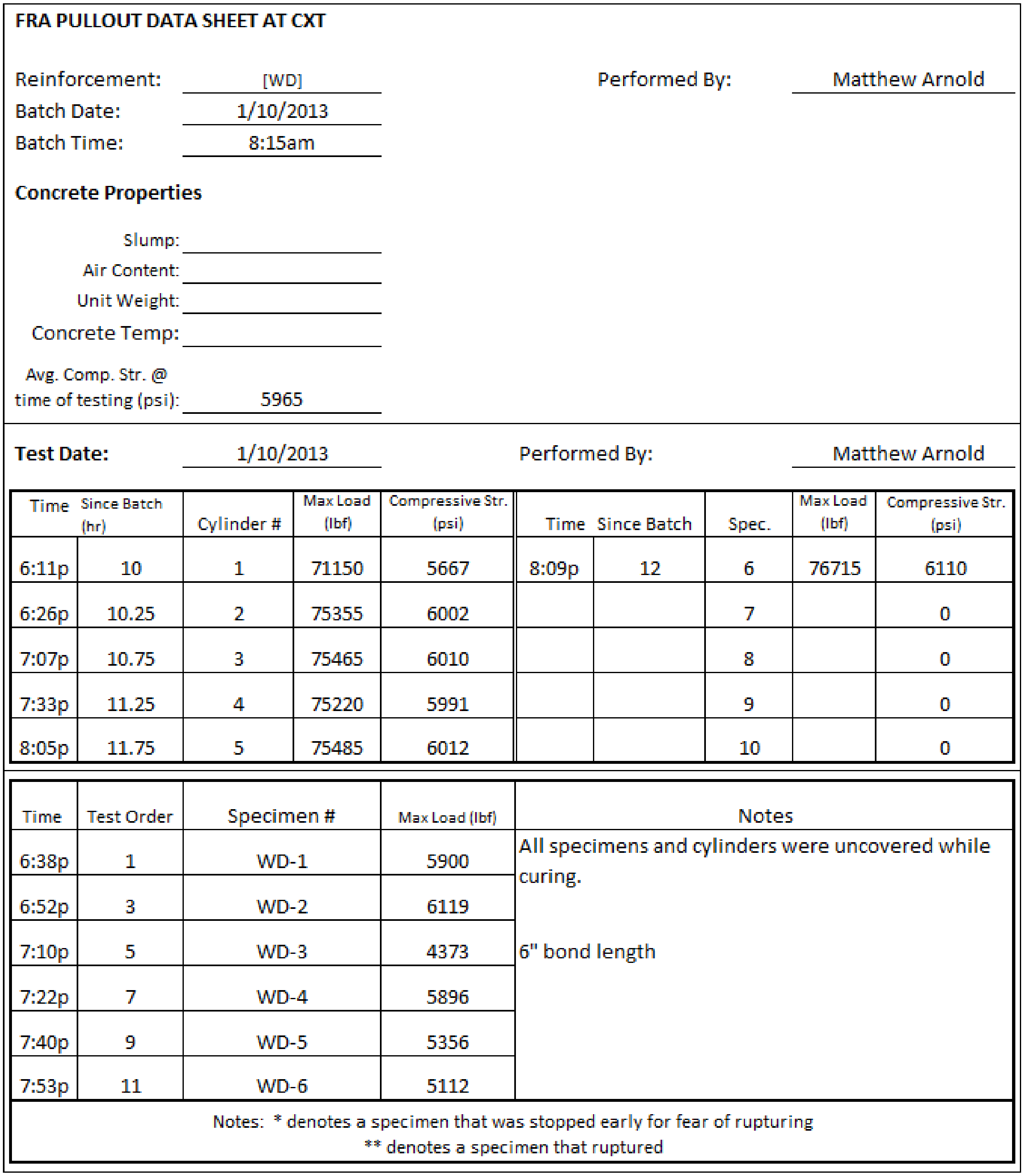
Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
12:32a	13.5	1	83205	6627			6		0
12:37a	13.5	2	81405	6483			7		0
1:36a	14.5	3	84400	6722			8		0
1:39a	14.5	4	82835	6597			9		0
		5		0			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
12"44a	1	WC-1	7480	All specimens and cylinders were covered while curing.
1:04a	3	WC-2	8665	
1:20a	5	WC-3	7497	6" bond length
1:33a	7	WC-4	9249 *	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M.3 As-received [WC] batch summary at CXT



FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [WD]
Performed By: Matthew Arnold
Batch Date: 1/10/2013
Batch Time: 8:15am

Concrete Properties

Slump:
Air Content:
Unit Weight:
Concrete Temp:
Avg. Comp. Str. @ time of testing (psi): 5965

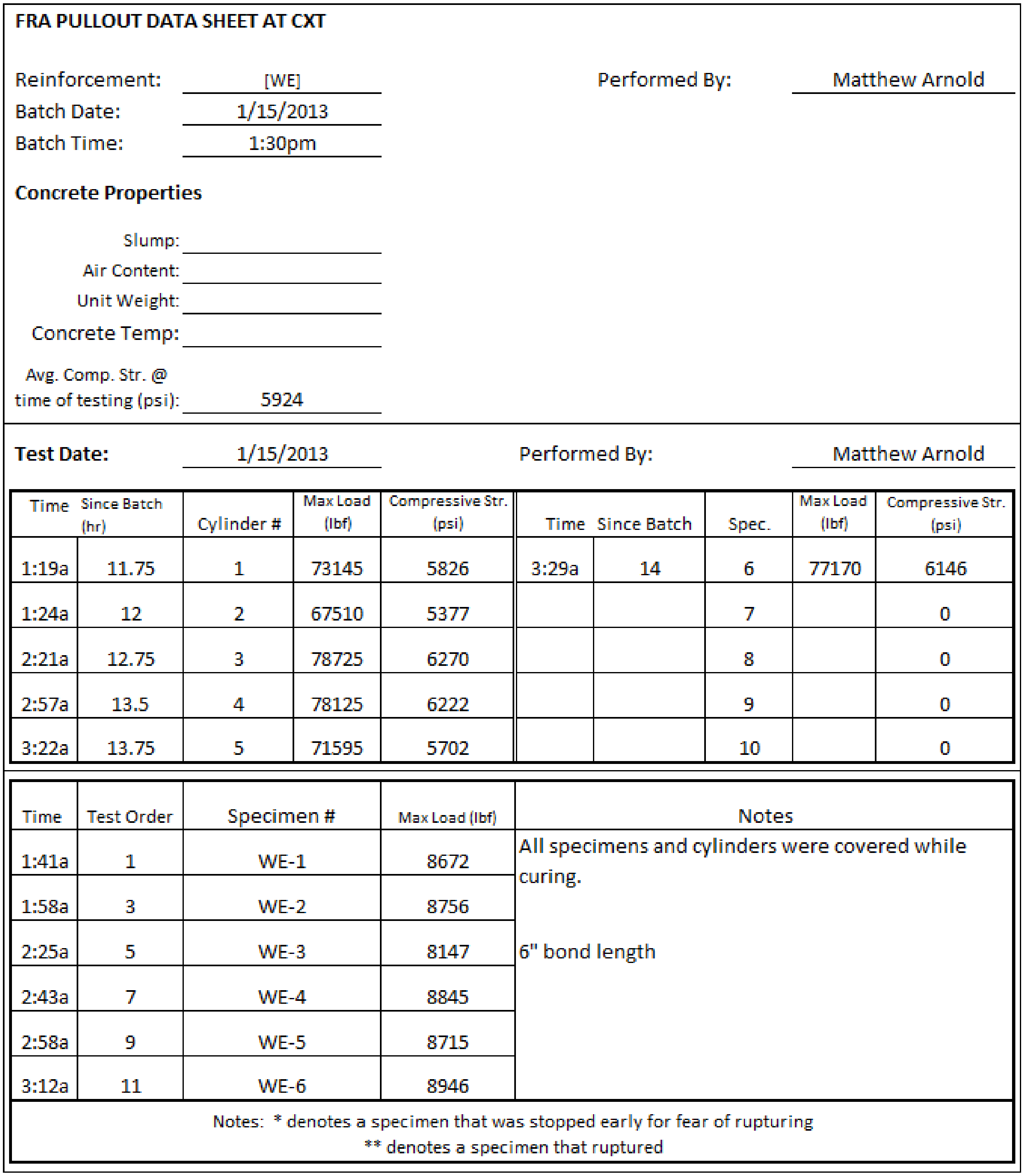
Test Date: 1/10/2013
Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
6:11p	10	1	71150	5667	8:09p	12	6	76715	6110
6:26p	10.25	2	75355	6002			7		0
7:07p	10.75	3	75465	6010			8		0
7:33p	11.25	4	75220	5991			9		0
8:05p	11.75	5	75485	6012			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
6:38p	1	WD-1	5900	All specimens and cylinders were uncovered while curing.
6:52p	3	WD-2	6119	
7:10p	5	WD-3	4373	6" bond length
7:22p	7	WD-4	5896	
7:40p	9	WD-5	5356	
7:53p	11	WD-6	5112	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M.4 As-received [WD] batch summary at CXT



FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [WE]
Batch Date: 1/15/2013
Batch Time: 1:30pm

Performed By: Matthew Arnold

Concrete Properties

Slump:
Air Content:
Unit Weight:
Concrete Temp:
Avg. Comp. Str. @ time of testing (psi): 5924

Test Date: 1/15/2013

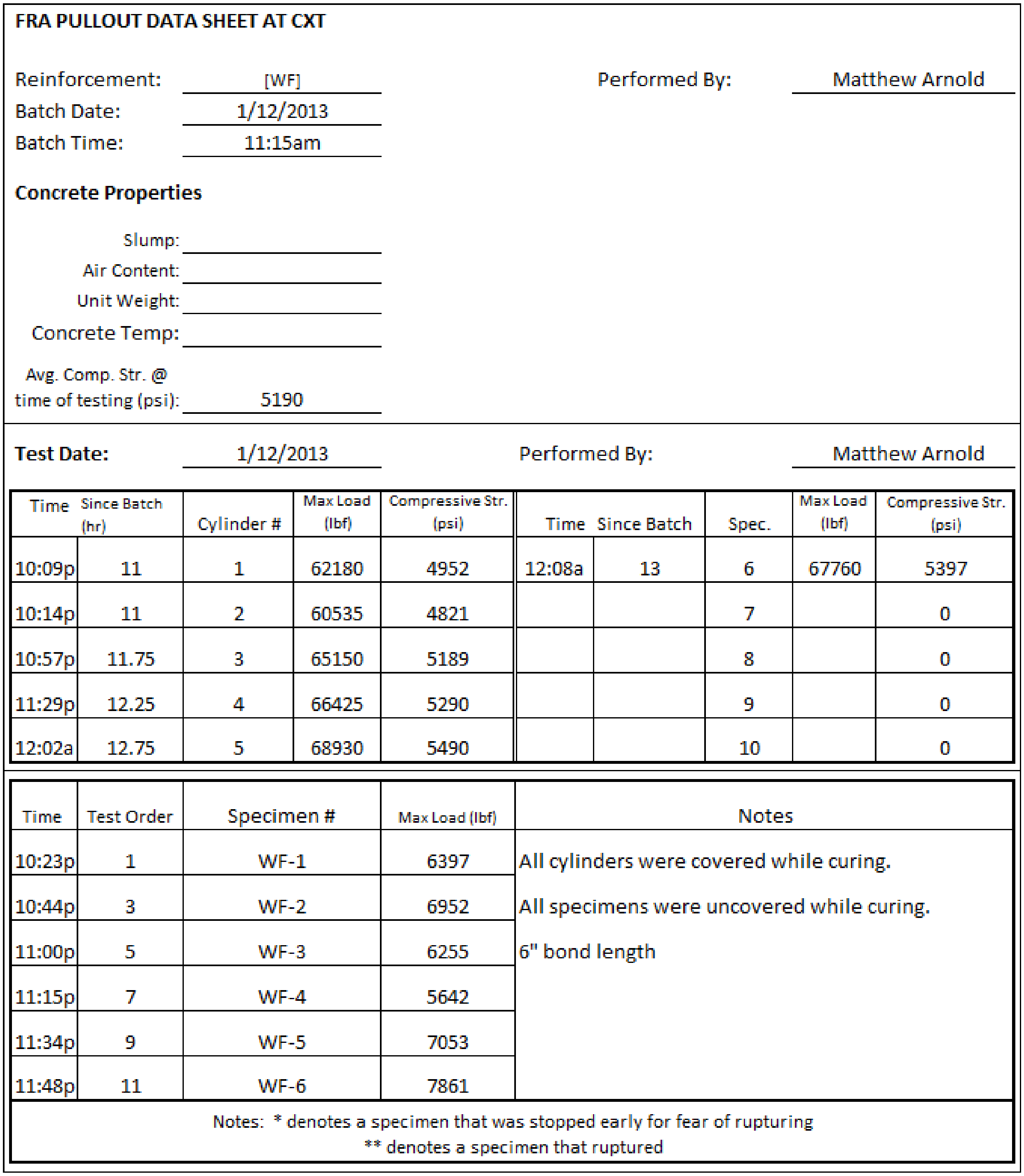
Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
1:19a	11.75	1	73145	5826	3:29a	14	6	77170	6146
1:24a	12	2	67510	5377			7		0
2:21a	12.75	3	78725	6270			8		0
2:57a	13.5	4	78125	6222			9		0
3:22a	13.75	5	71595	5702			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
1:41a	1	WE-1	8672	All specimens and cylinders were covered while curing.
1:58a	3	WE-2	8756	
2:25a	5	WE-3	8147	6" bond length
2:43a	7	WE-4	8845	
2:58a	9	WE-5	8715	
3:12a	11	WE-6	8946	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M.5 As-received [WE] batch summary at CXT



FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [WF]
Batch Date: 1/12/2013
Batch Time: 11:15am

Performed By: Matthew Arnold

Concrete Properties

Slump:
Air Content:
Unit Weight:
Concrete Temp:
Avg. Comp. Str. @ time of testing (psi): 5190

Test Date: 1/12/2013

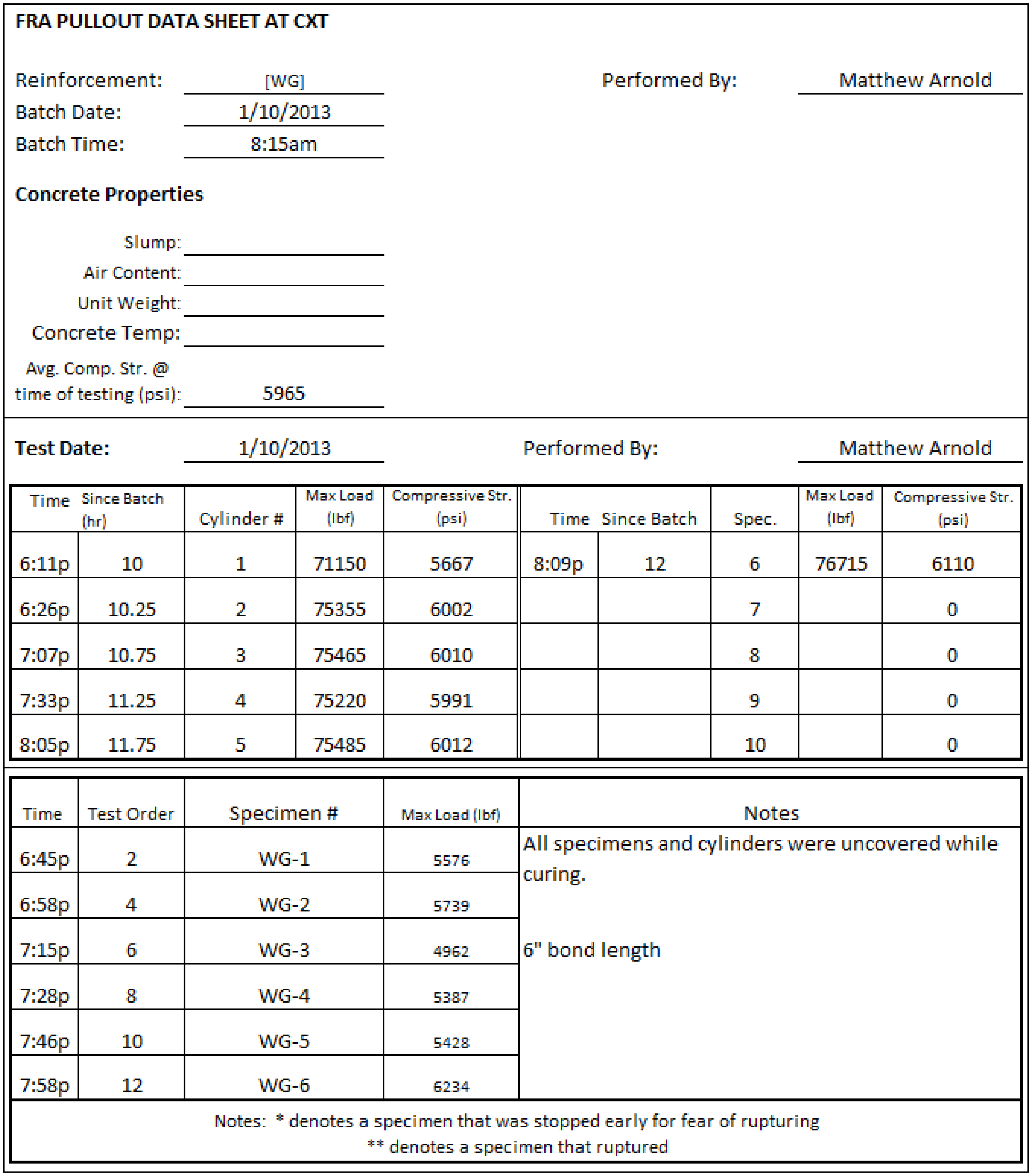
Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
10:09p	11	1	62180	4952	12:08a	13	6	67760	5397
10:14p	11	2	60535	4821			7		0
10:57p	11.75	3	65150	5189			8		0
11:29p	12.25	4	66425	5290			9		0
12:02a	12.75	5	68930	5490			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
10:23p	1	WF-1	6397	All cylinders were covered while curing.
10:44p	3	WF-2	6952	All specimens were uncovered while curing.
11:00p	5	WF-3	6255	6" bond length
11:15p	7	WF-4	5642	
11:34p	9	WF-5	7053	
11:48p	11	WF-6	7861	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M.6 As-received [WF] batch summary at CXT



FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [WG]

Performed By: Matthew Arnold

Batch Date: 1/10/2013

Batch Time: 8:15am

Concrete Properties

Slump:

Air Content:

Unit Weight:

Concrete Temp:

Avg. Comp. Str. @ time of testing (psi): 5965

Test Date: 1/10/2013

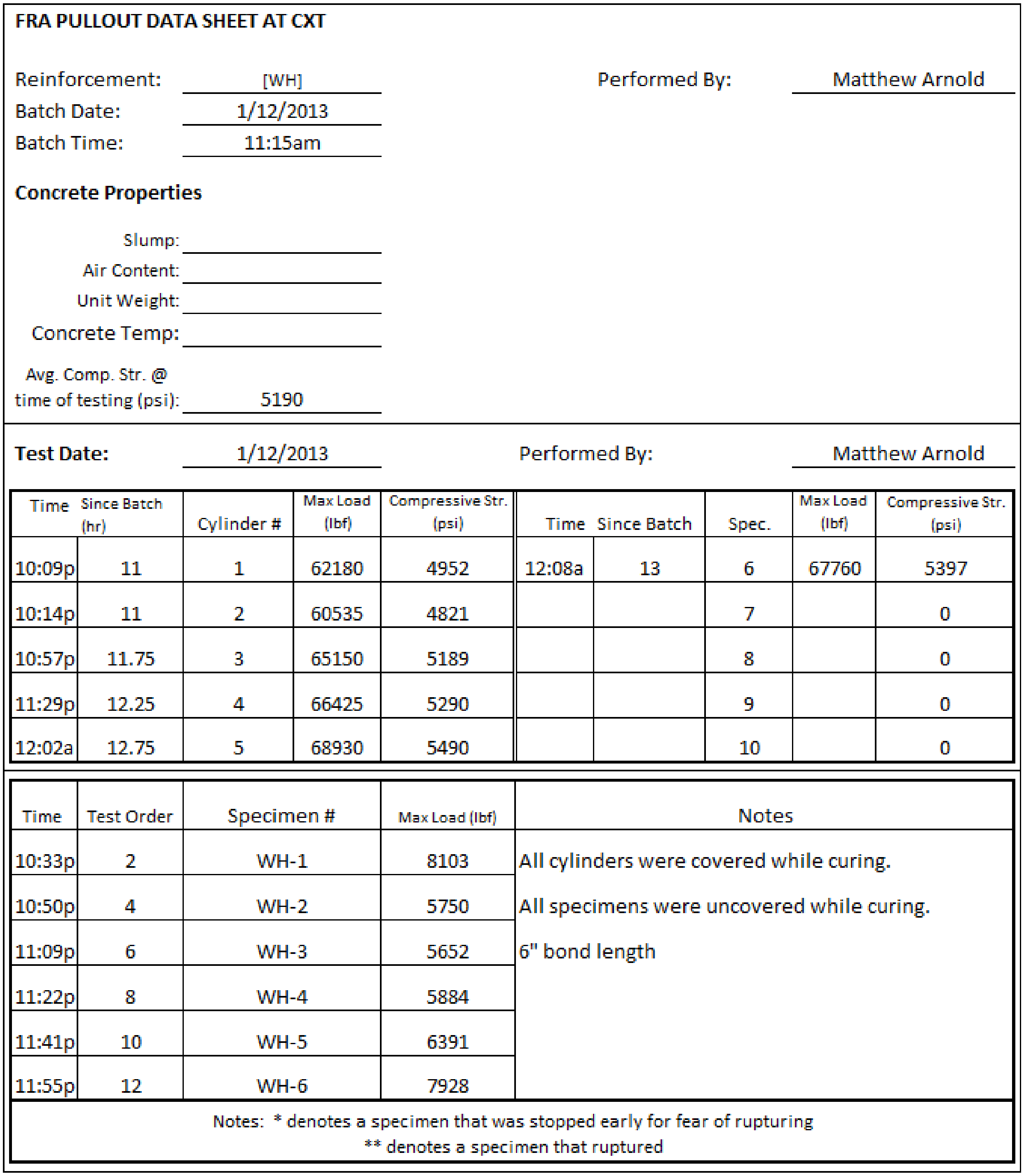
Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
6:11p	10	1	71150	5667	8:09p	12	6	76715	6110
6:26p	10.25	2	75355	6002			7		0
7:07p	10.75	3	75465	6010			8		0
7:33p	11.25	4	75220	5991			9		0
8:05p	11.75	5	75485	6012			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
6:45p	2	WG-1	5576	All specimens and cylinders were uncovered while curing.
6:58p	4	WG-2	5739	
7:15p	6	WG-3	4962	6" bond length
7:28p	8	WG-4	5387	
7:46p	10	WG-5	5428	
7:58p	12	WG-6	6234	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M.7 As-received [WG] batch summary at CXT



FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [WH]

Performed By: Matthew Arnold

Batch Date: 1/12/2013

Batch Time: 11:15am

Concrete Properties

Slump:

Air Content:

Unit Weight:

Concrete Temp:

Avg. Comp. Str. @ time of testing (psi): 5190

Test Date: 1/12/2013

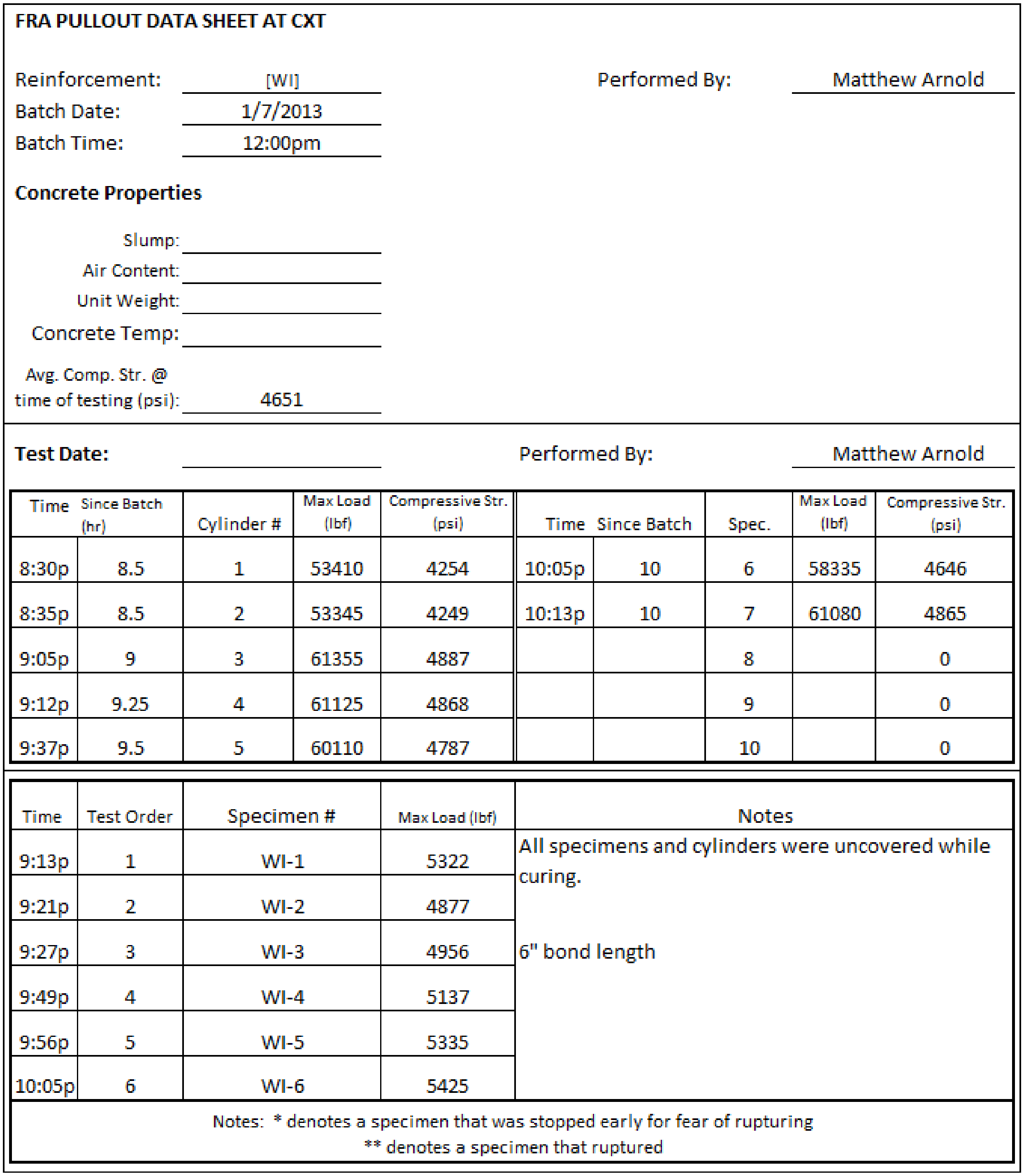
Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
10:09p	11	1	62180	4952	12:08a	13	6	67760	5397
10:14p	11	2	60535	4821			7		0
10:57p	11.75	3	65150	5189			8		0
11:29p	12.25	4	66425	5290			9		0
12:02a	12.75	5	68930	5490			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
10:33p	2	WH-1	8103	All cylinders were covered while curing.
10:50p	4	WH-2	5750	All specimens were uncovered while curing.
11:09p	6	WH-3	5652	6" bond length
11:22p	8	WH-4	5884	
11:41p	10	WH-5	6391	
11:55p	12	WH-6	7928	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M.8 As-received [WH] batch summary at CXT



FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [WI]
Batch Date: 1/7/2013
Batch Time: 12:00pm
Performed By: Matthew Arnold

Concrete Properties

Slump:
Air Content:
Unit Weight:
Concrete Temp:
Avg. Comp. Str. @ time of testing (psi): 4651

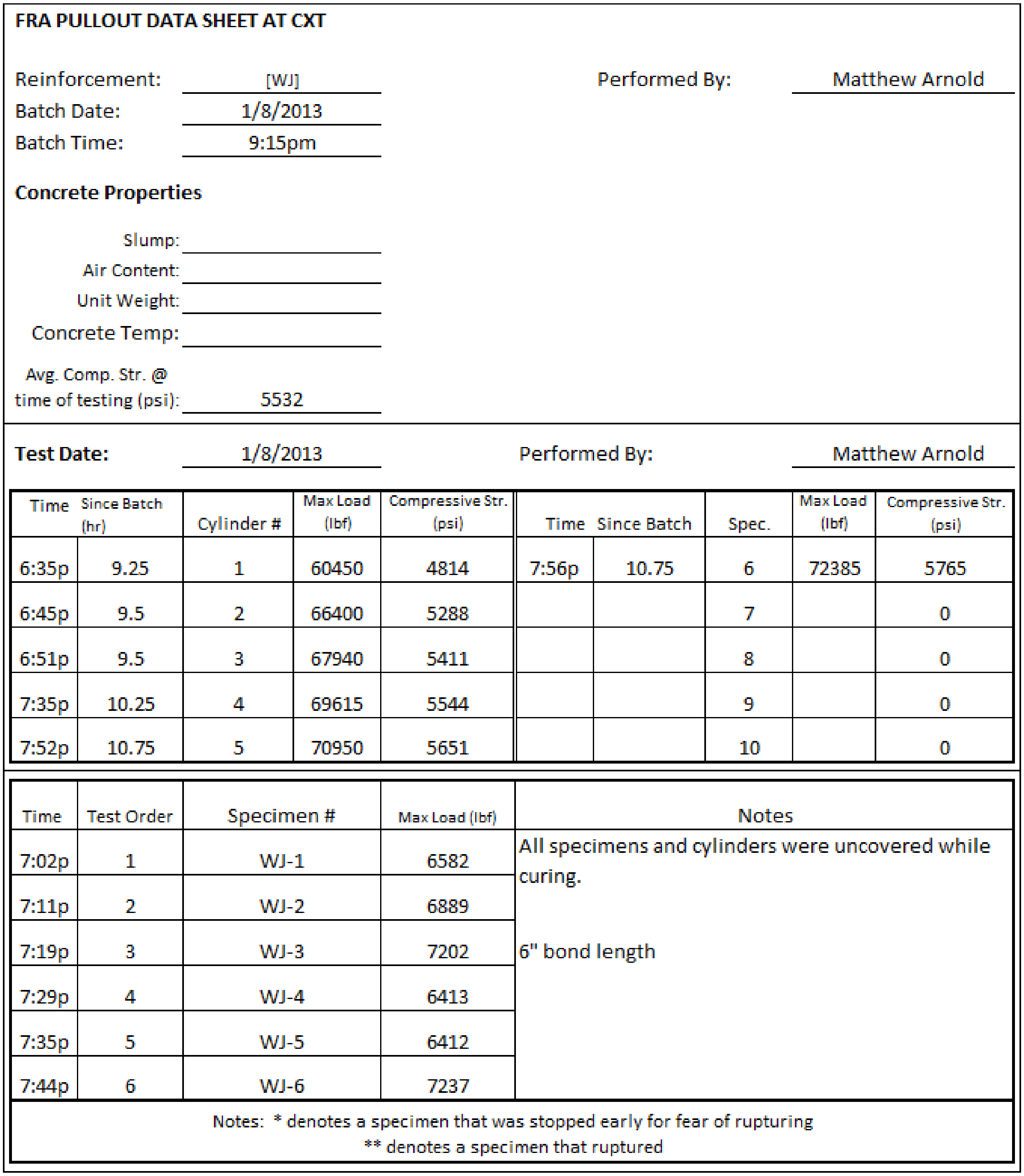
Test Date:
Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
8:30p	8.5	1	53410	4254	10:05p	10	6	58335	4646
8:35p	8.5	2	53345	4249	10:13p	10	7	61080	4865
9:05p	9	3	61355	4887			8		0
9:12p	9.25	4	61125	4868			9		0
9:37p	9.5	5	60110	4787			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
9:13p	1	WI-1	5322	All specimens and cylinders were uncovered while curing.
9:21p	2	WI-2	4877	
9:27p	3	WI-3	4956	6" bond length
9:49p	4	WI-4	5137	
9:56p	5	WI-5	5335	
10:05p	6	WI-6	5425	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M.9 As-received [WI] batch summary at CXT



FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [WJ]
Batch Date: 1/8/2013
Batch Time: 9:15pm
Performed By: Matthew Arnold

Concrete Properties

Slump:
Air Content:
Unit Weight:
Concrete Temp:
Avg. Comp. Str. @ time of testing (psi): 5532

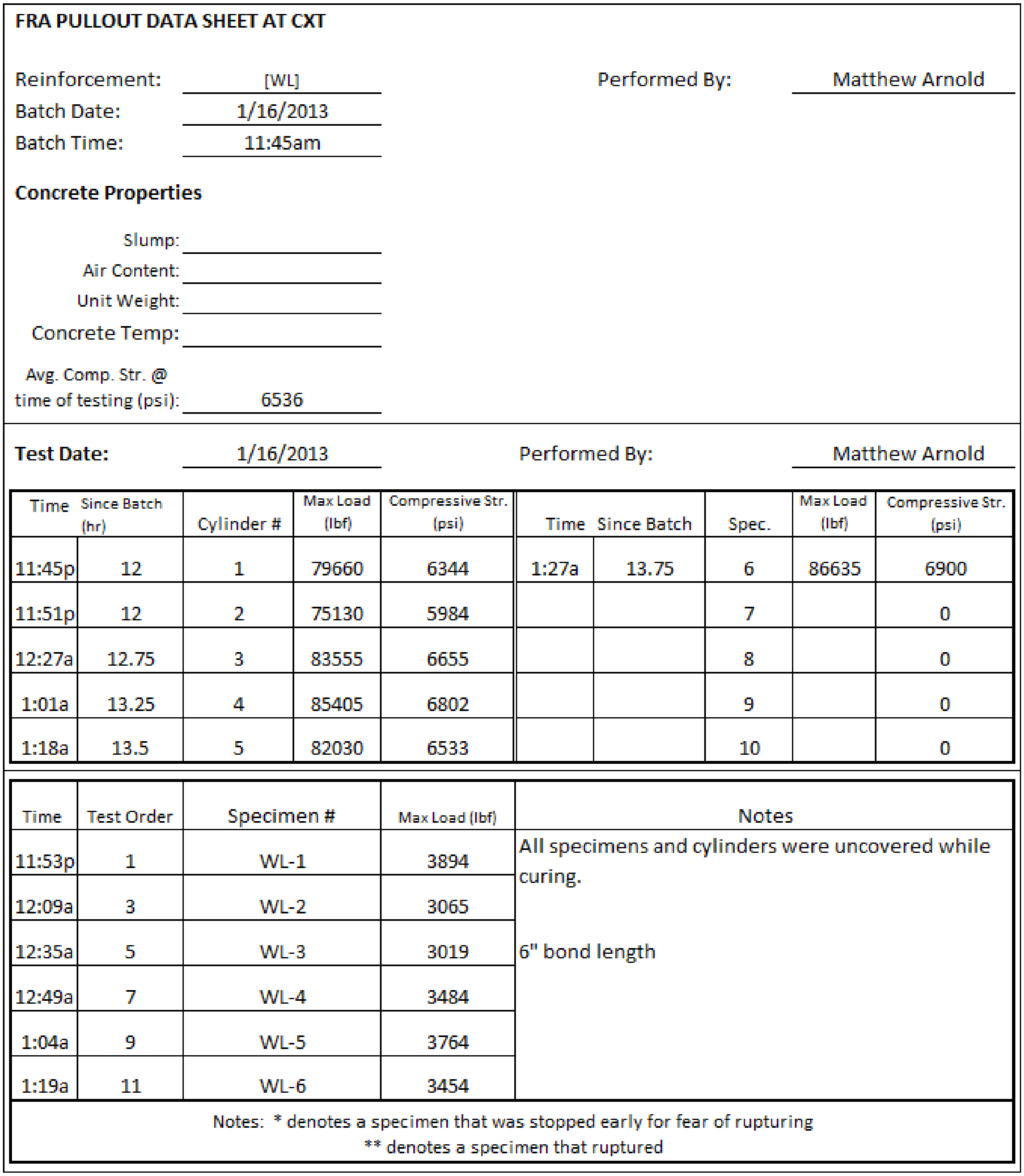
Test Date: 1/8/2013
Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
6:35p	9.25	1	60450	4814	7:56p	10.75	6	72385	5765
6:45p	9.5	2	66400	5288			7		0
6:51p	9.5	3	67940	5411			8		0
7:35p	10.25	4	69615	5544			9		0
7:52p	10.75	5	70950	5651			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
7:02p	1	WJ-1	6582	All specimens and cylinders were uncovered while curing.
7:11p	2	WJ-2	6889	
7:19p	3	WJ-3	7202	6" bond length
7:29p	4	WJ-4	6413	
7:35p	5	WJ-5	6412	
7:44p	6	WJ-6	7237	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M.10 As-received [WJ] batch summary at CXT



FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [WL]

Performed By: Matthew Arnold

Batch Date: 1/16/2013

Batch Time: 11:45am

Concrete Properties

Slump:

Air Content:

Unit Weight:

Concrete Temp:

Avg. Comp. Str. @ time of testing (psi): 6536

Test Date: 1/16/2013

Performed By: Matthew Arnold

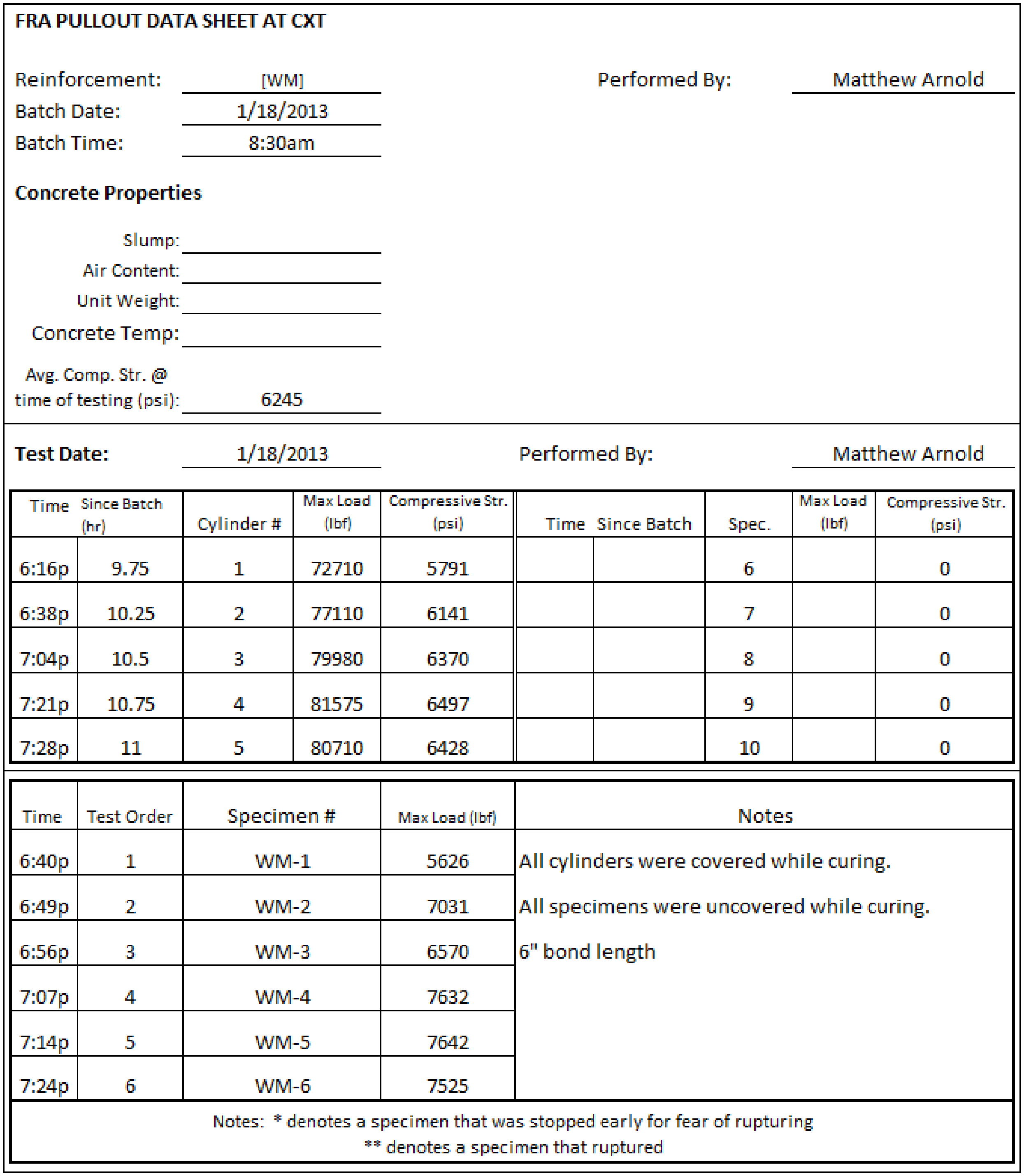
Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
11:45p	12	1	79660	6344	1:27a	13.75	6	86635	6900
11:51p	12	2	75130	5984			7		0
12:27a	12.75	3	83555	6655			8		0
1:01a	13.25	4	85405	6802			9		0
1:18a	13.5	5	82030	6533			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
11:53p	1	WL-1	3894	All specimens and cylinders were uncovered while curing.
12:09a	3	WL-2	3065	
12:35a	5	WL-3	3019	6" bond length
12:49a	7	WL-4	3484	
1:04a	9	WL-5	3764	
1:19a	11	WL-6	3454	

Notes: * denotes a specimen that was stopped early for fear of rupturing

** denotes a specimen that ruptured

Figure M.11 As-received [WL] batch summary at CXT



FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [WM]

Performed By: Matthew Arnold

Batch Date: 1/18/2013

Batch Time: 8:30am

Concrete Properties

Slump:

Air Content:

Unit Weight:

Concrete Temp:

Avg. Comp. Str. @ time of testing (psi): 6245

Test Date: 1/18/2013

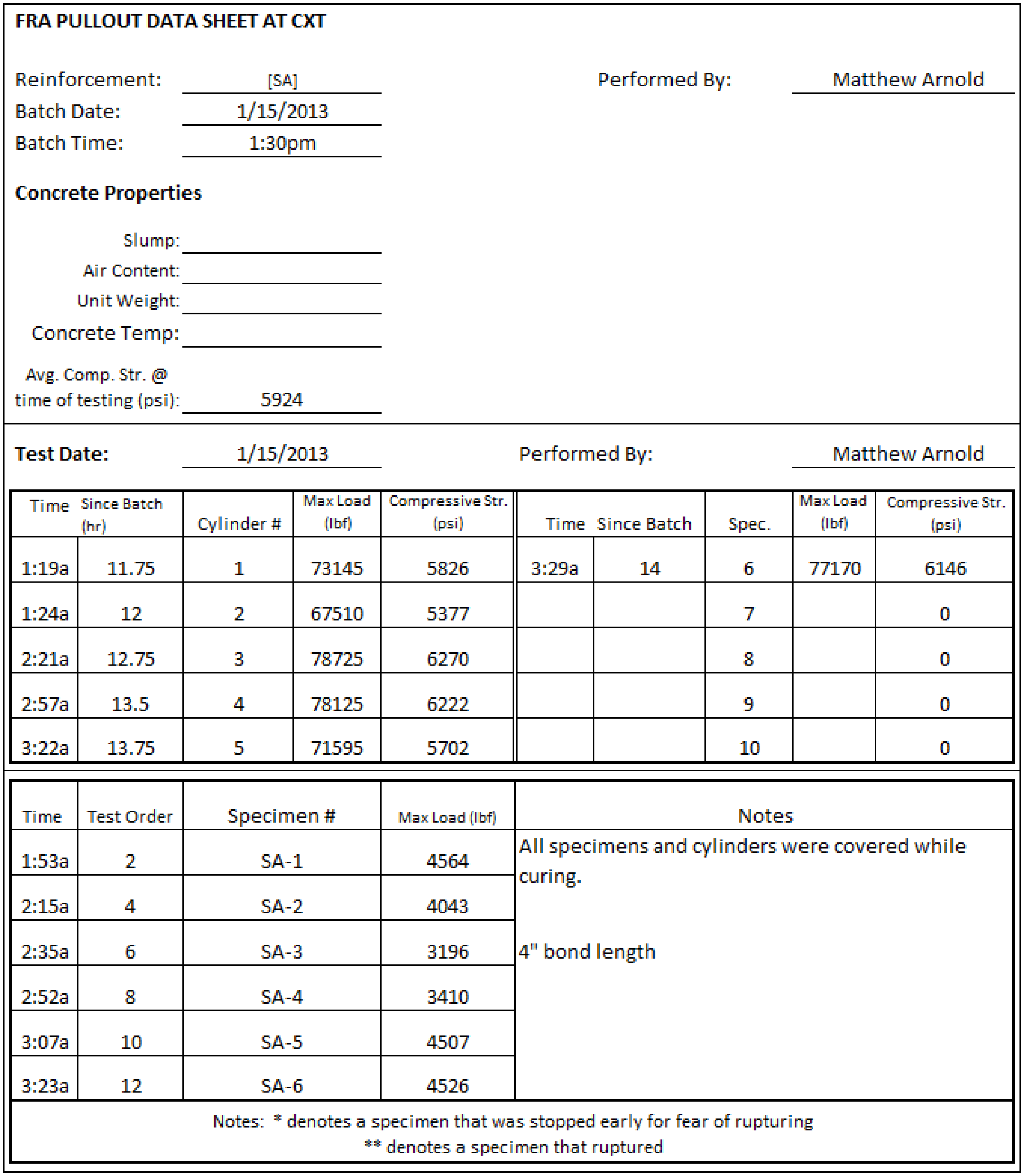
Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
6:16p	9.75	1	72710	5791			6		0
6:38p	10.25	2	77110	6141			7		0
7:04p	10.5	3	79980	6370			8		0
7:21p	10.75	4	81575	6497			9		0
7:28p	11	5	80710	6428			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
6:40p	1	WM-1	5626	All cylinders were covered while curing.
6:49p	2	WM-2	7031	All specimens were uncovered while curing.
6:56p	3	WM-3	6570	6" bond length
7:07p	4	WM-4	7632	
7:14p	5	WM-5	7642	
7:24p	6	WM-6	7525	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M.12 As-received [WM] batch summary at CXT



FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [SA]

Performed By: Matthew Arnold

Batch Date: 1/15/2013

Batch Time: 1:30pm

Concrete Properties

Slump:

Air Content:

Unit Weight:

Concrete Temp:

Avg. Comp. Str. @ time of testing (psi): 5924

Test Date: 1/15/2013

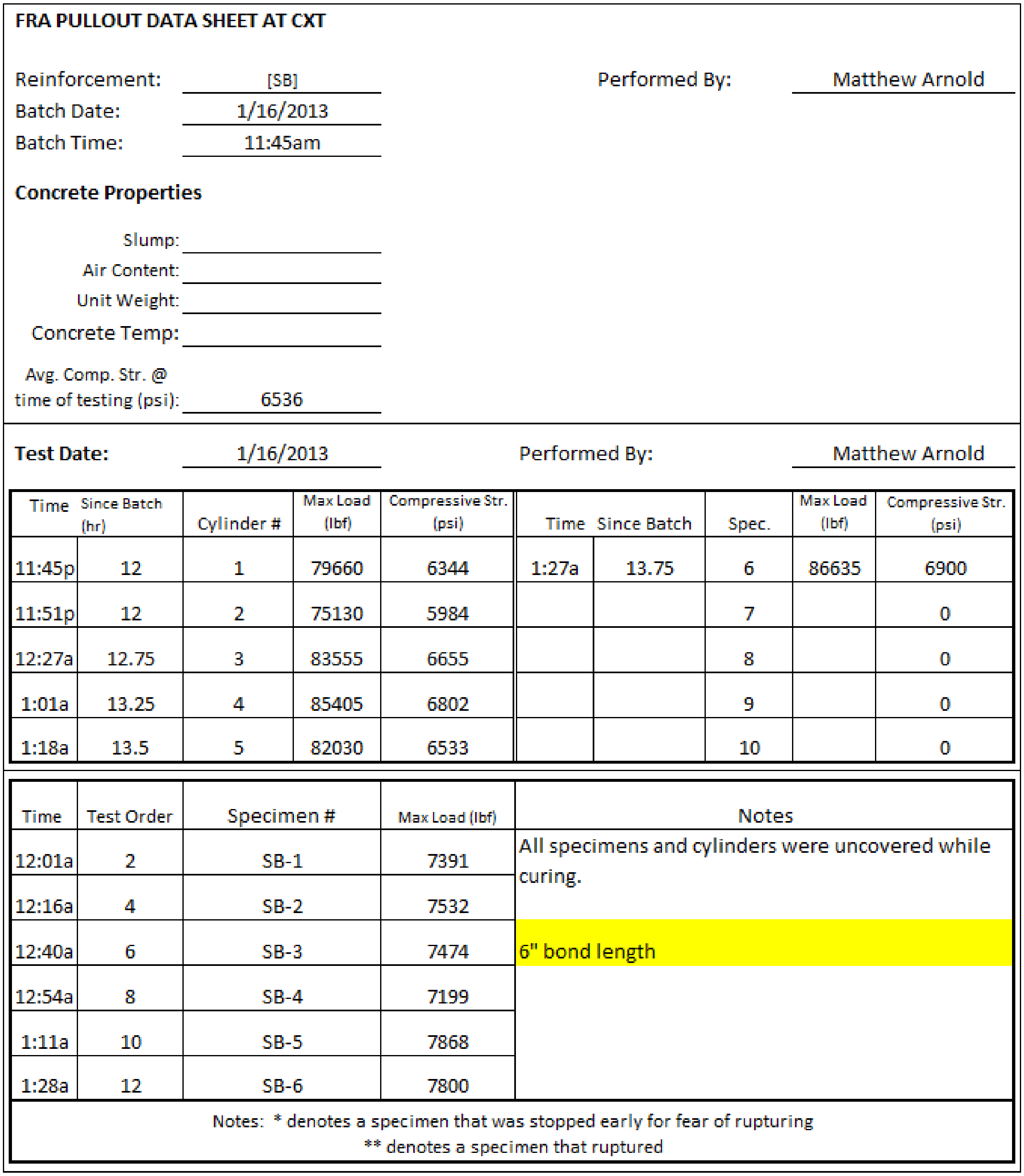
Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
1:19a	11.75	1	73145	5826	3:29a	14	6	77170	6146
1:24a	12	2	67510	5377			7		0
2:21a	12.75	3	78725	6270			8		0
2:57a	13.5	4	78125	6222			9		0
3:22a	13.75	5	71595	5702			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
1:53a	2	SA-1	4564	All specimens and cylinders were covered while curing.
2:15a	4	SA-2	4043	
2:35a	6	SA-3	3196	4" bond length
2:52a	8	SA-4	3410	
3:07a	10	SA-5	4507	
3:23a	12	SA-6	4526	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M.13 As-received [SA] batch summary at CXT



FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [SB]

Performed By: Matthew Arnold

Batch Date: 1/16/2013

Batch Time: 11:45am

Concrete Properties

Slump:

Air Content:

Unit Weight:

Concrete Temp:

Avg. Comp. Str. @ time of testing (psi): 6536

Test Date: 1/16/2013

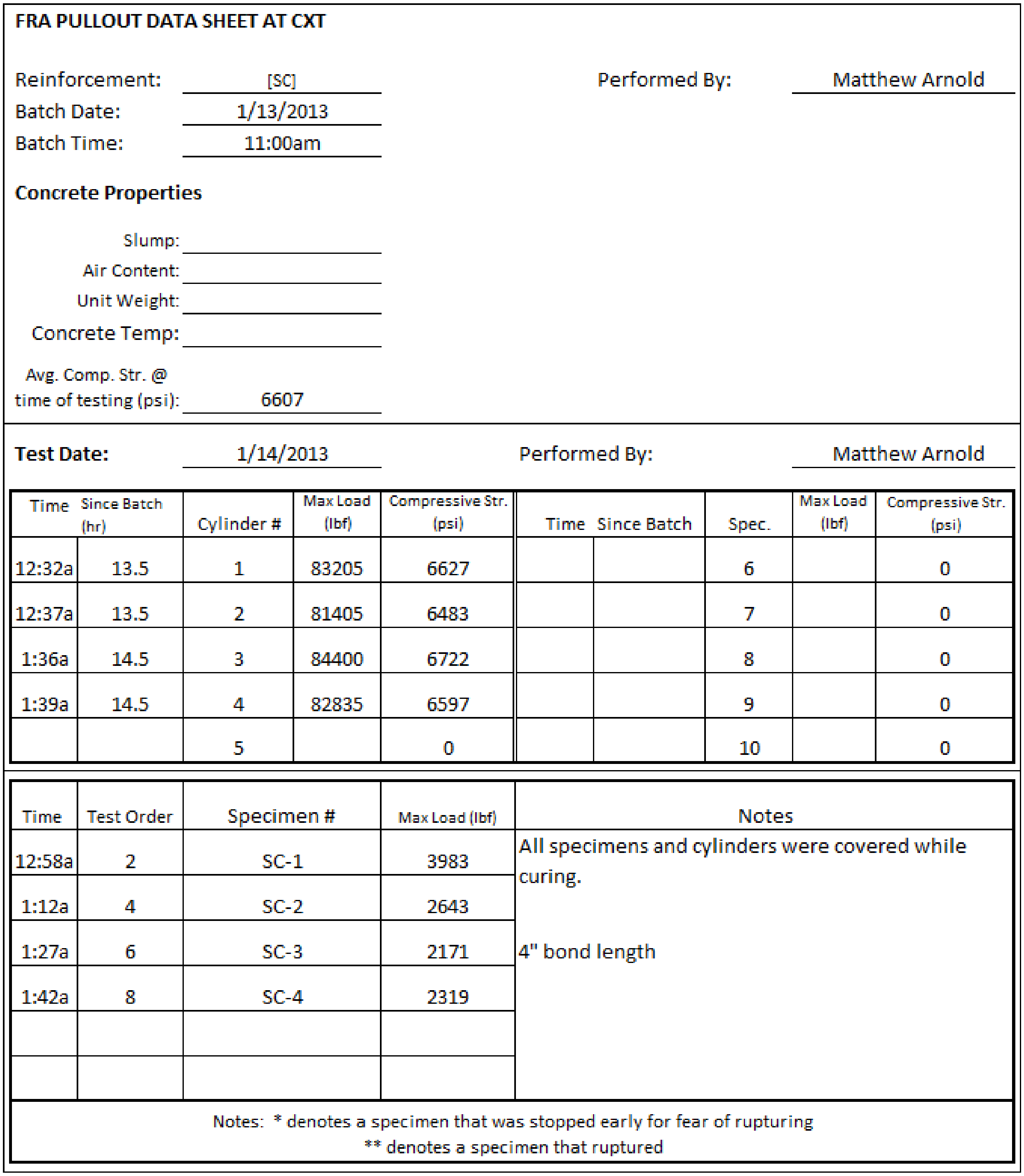
Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
11:45p	12	1	79660	6344	1:27a	13.75	6	86635	6900
11:51p	12	2	75130	5984			7		0
12:27a	12.75	3	83555	6655			8		0
1:01a	13.25	4	85405	6802			9		0
1:18a	13.5	5	82030	6533			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
12:01a	2	SB-1	7391	All specimens and cylinders were uncovered while curing.
12:16a	4	SB-2	7532	
12:40a	6	SB-3	7474	6" bond length
12:54a	8	SB-4	7199	
1:11a	10	SB-5	7868	
1:28a	12	SB-6	7800	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M.14 As-received [SB] batch summary at CXT



FRA PULLOUT DATA SHEET AT CXT

Reinforcement: [SC]

Performed By: Matthew Arnold

Batch Date: 1/13/2013

Batch Time: 11:00am

Concrete Properties

Slump:

Air Content:

Unit Weight:

Concrete Temp:

Avg. Comp. Str. @ time of testing (psi): 6607

Test Date: 1/14/2013

Performed By: Matthew Arnold

Time	Since Batch (hr)	Cylinder #	Max Load (lbf)	Compressive Str. (psi)	Time	Since Batch	Spec.	Max Load (lbf)	Compressive Str. (psi)
12:32a	13.5	1	83205	6627			6		0
12:37a	13.5	2	81405	6483			7		0
1:36a	14.5	3	84400	6722			8		0
1:39a	14.5	4	82835	6597			9		0
		5		0			10		0

Time	Test Order	Specimen #	Max Load (lbf)	Notes
12:58a	2	SC-1	3983	All specimens and cylinders were covered while curing. 4" bond length
1:12a	4	SC-2	2643	
1:27a	6	SC-3	2171	
1:42a	8	SC-4	2319	

Notes: * denotes a specimen that was stopped early for fear of rupturing
** denotes a specimen that ruptured

Figure M.15 As-received [SC] batch summary at CXT

Appendix N - Plant Phase, Wire and Strand; Individual Pullout Graphs

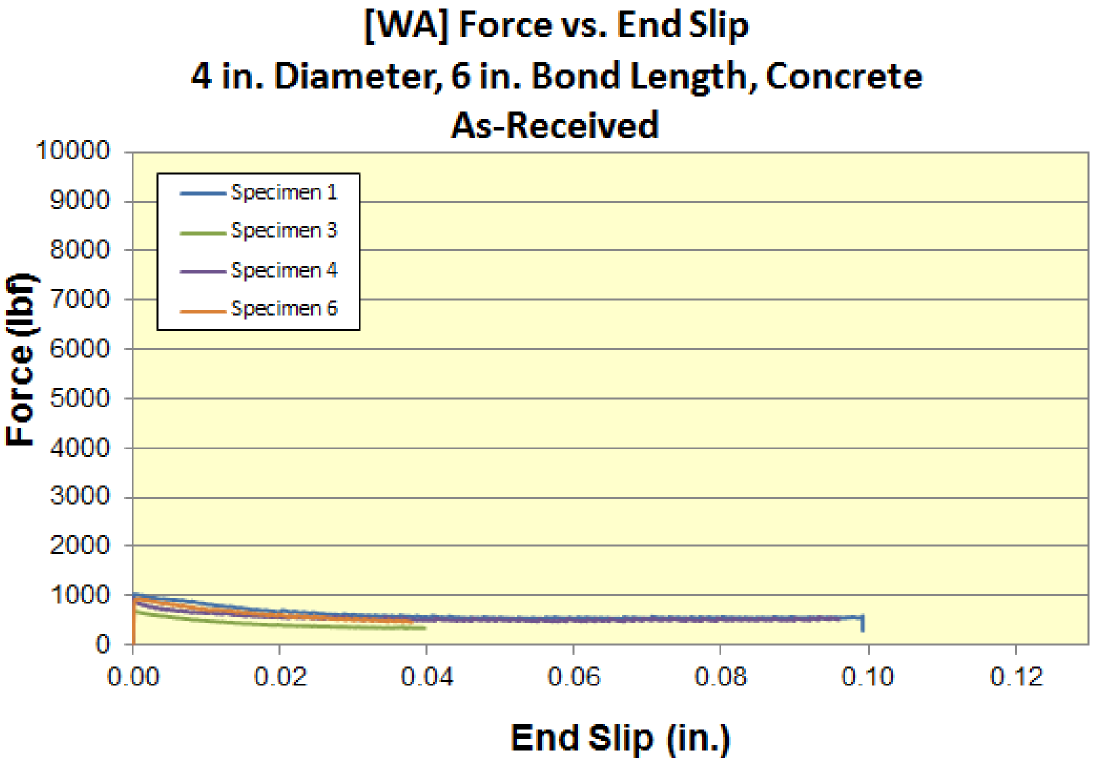


Figure N.1 As-received [WA] force vs. end slip individual graphs at CXT

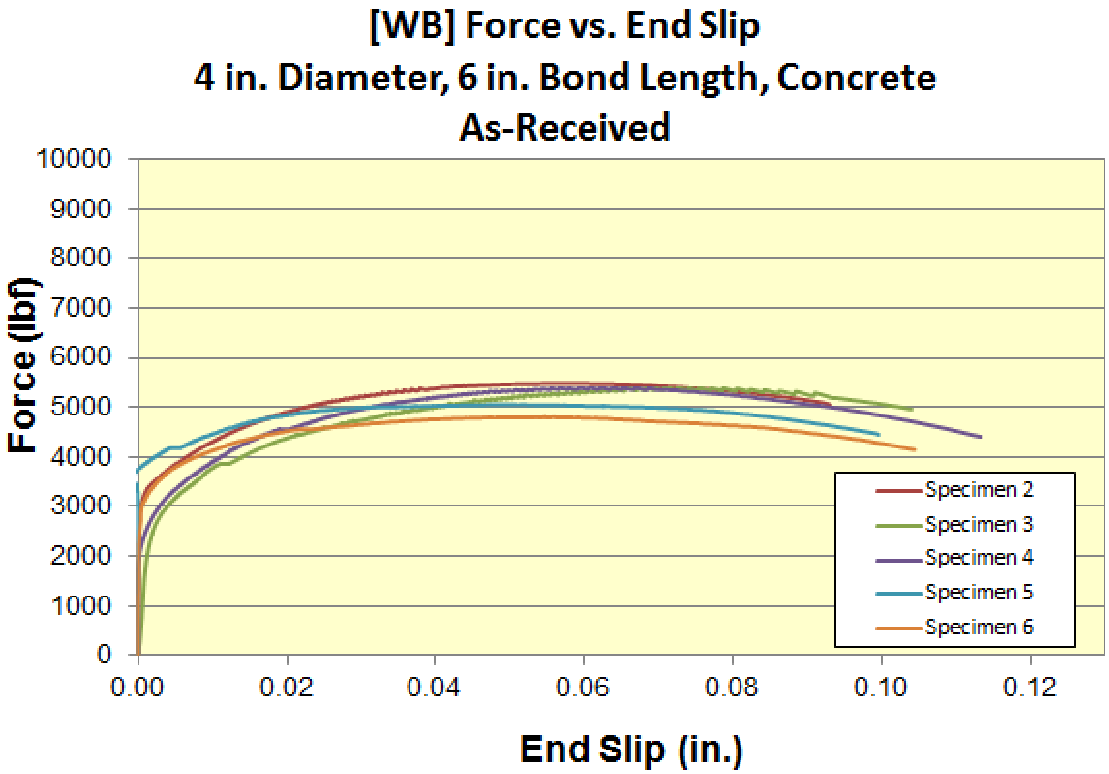


Figure N.2 As-received [WB] force vs. end slip individual graphs at CXT

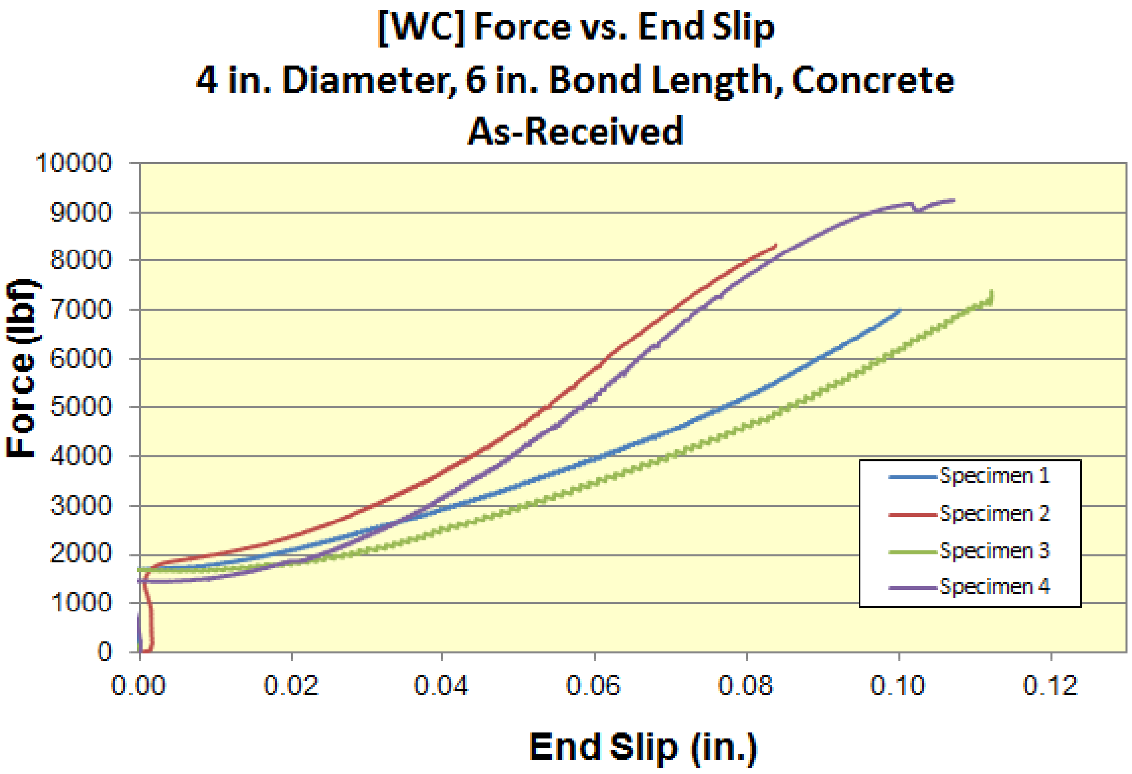


Figure N.3 As-received [WC] force vs. end slip individual graphs at CXT

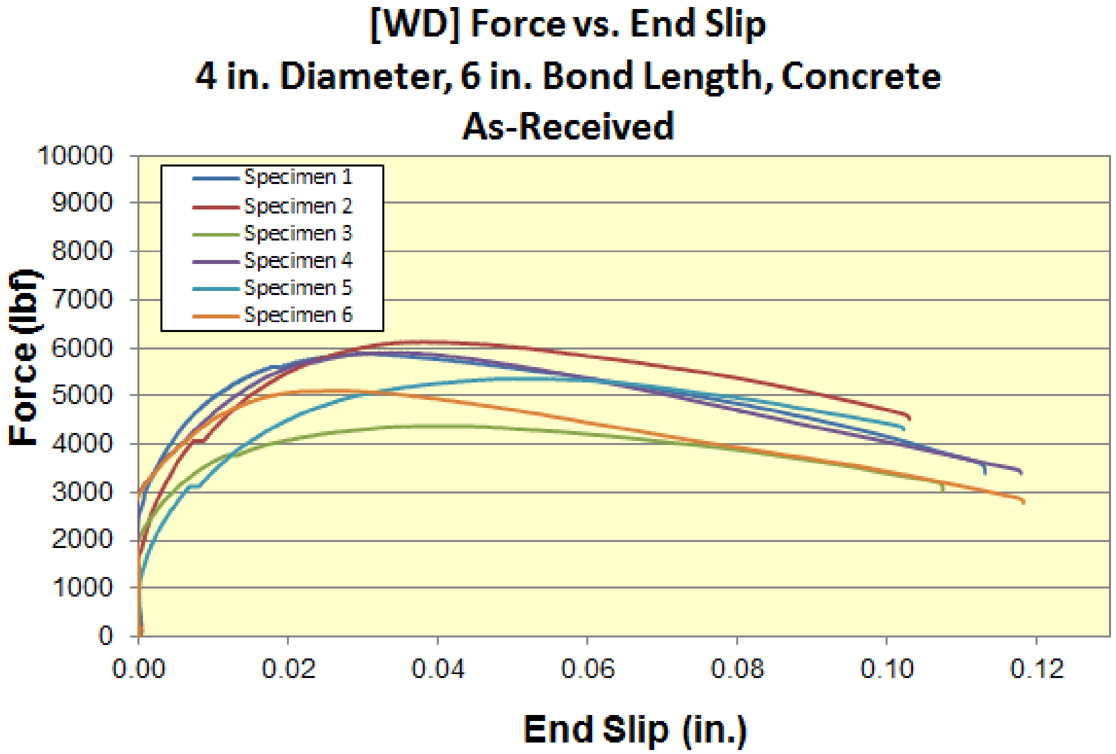


Figure N.4 As-received [WD] force vs. end slip individual graphs at CXT

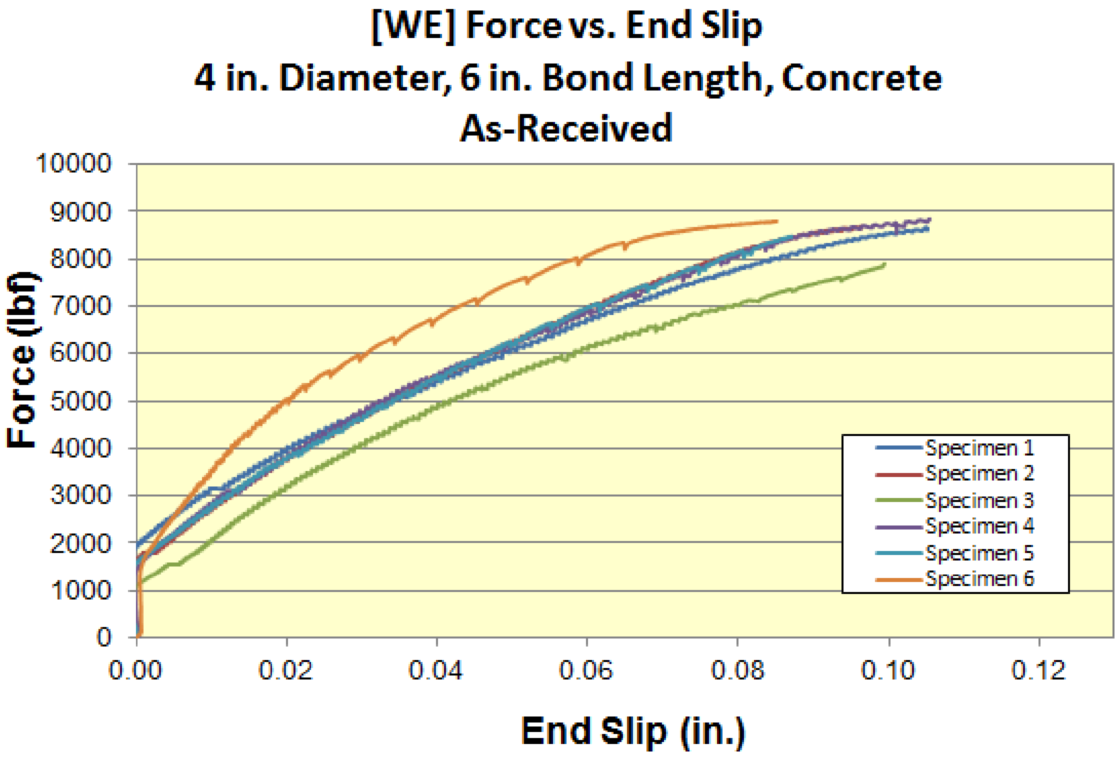


Figure N.5 As-received [WE] force vs. end slip individual graphs at CXT

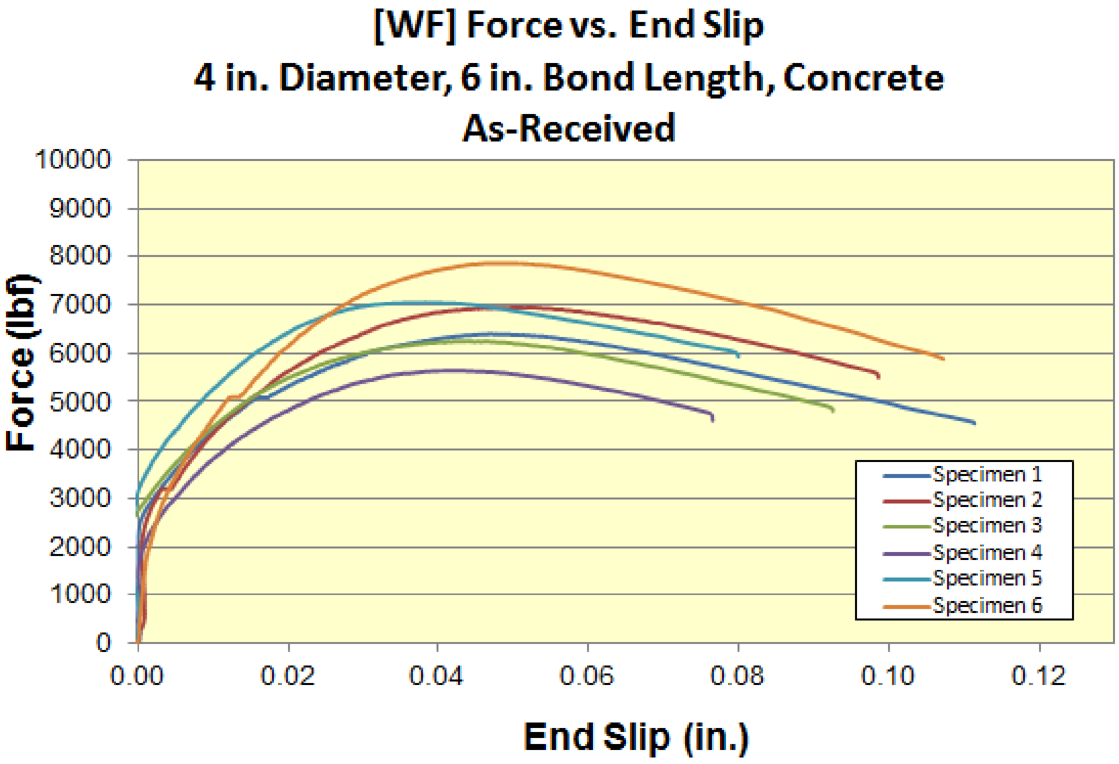


Figure N.6 As-received [WF] force vs. end slip individual graphs at CXT

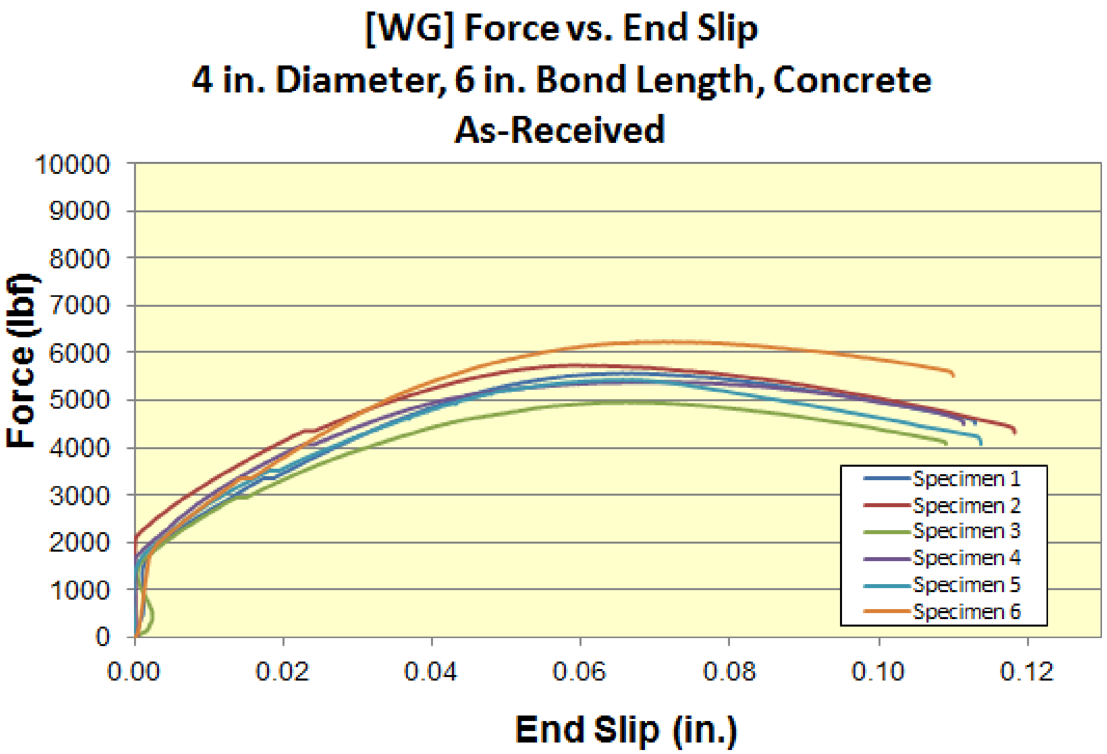


Figure N.7 As-received [WG] force vs. end slip individual graphs at CXT

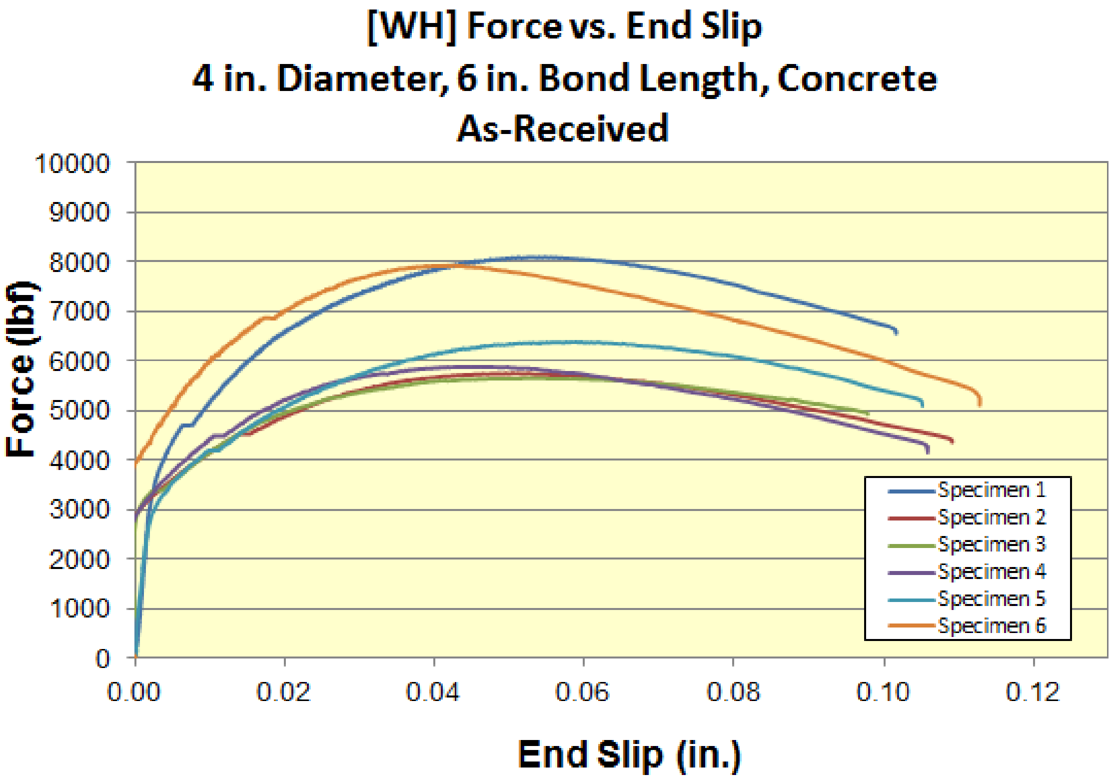


Figure N.8 As-received [WH] force vs. end slip individual graphs at CXT

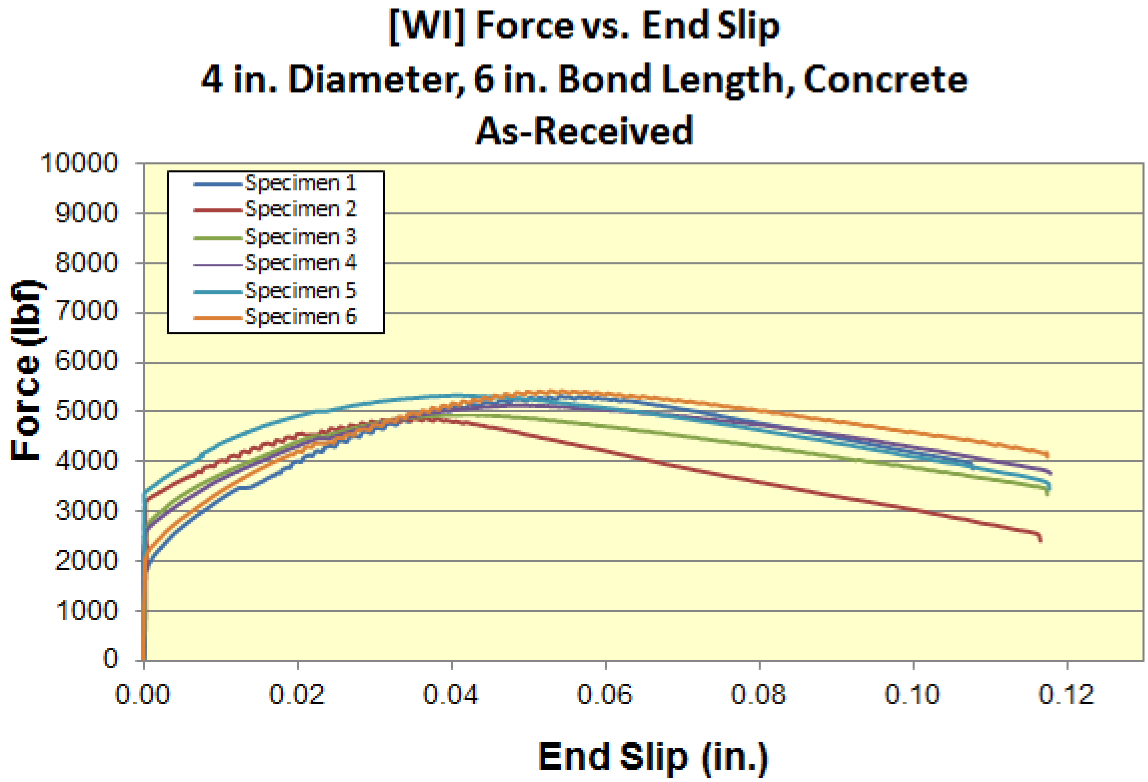


Figure N.9 As-received [WI] force vs. end slip individual graphs at CXT

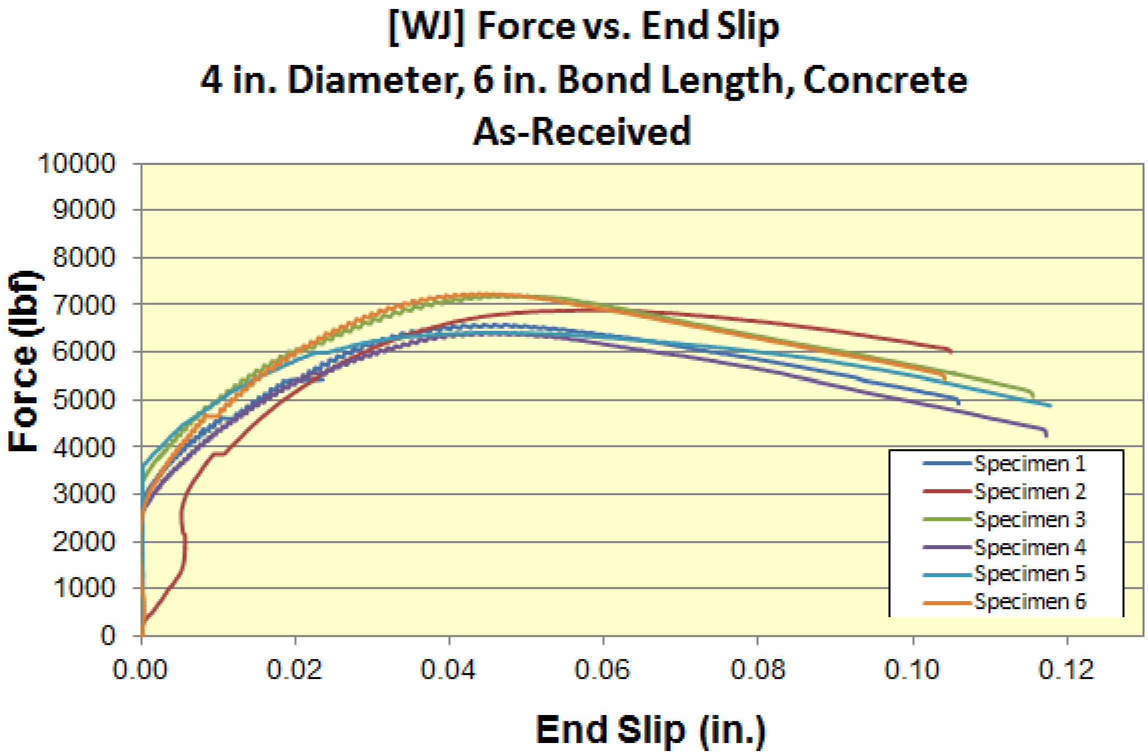


Figure N.10 As-received [WJ] force vs. end slip individual graphs at CXT

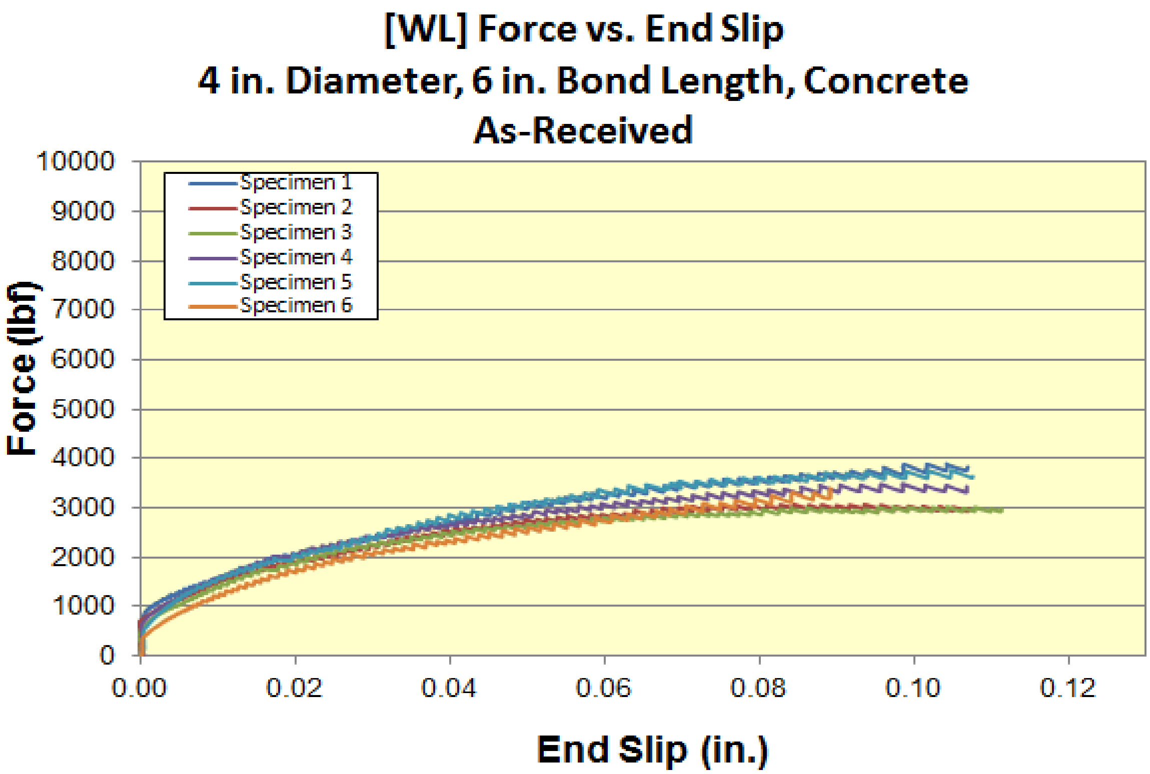


Figure N.11 As-received [WL] force vs. end slip individual graphs at CXT

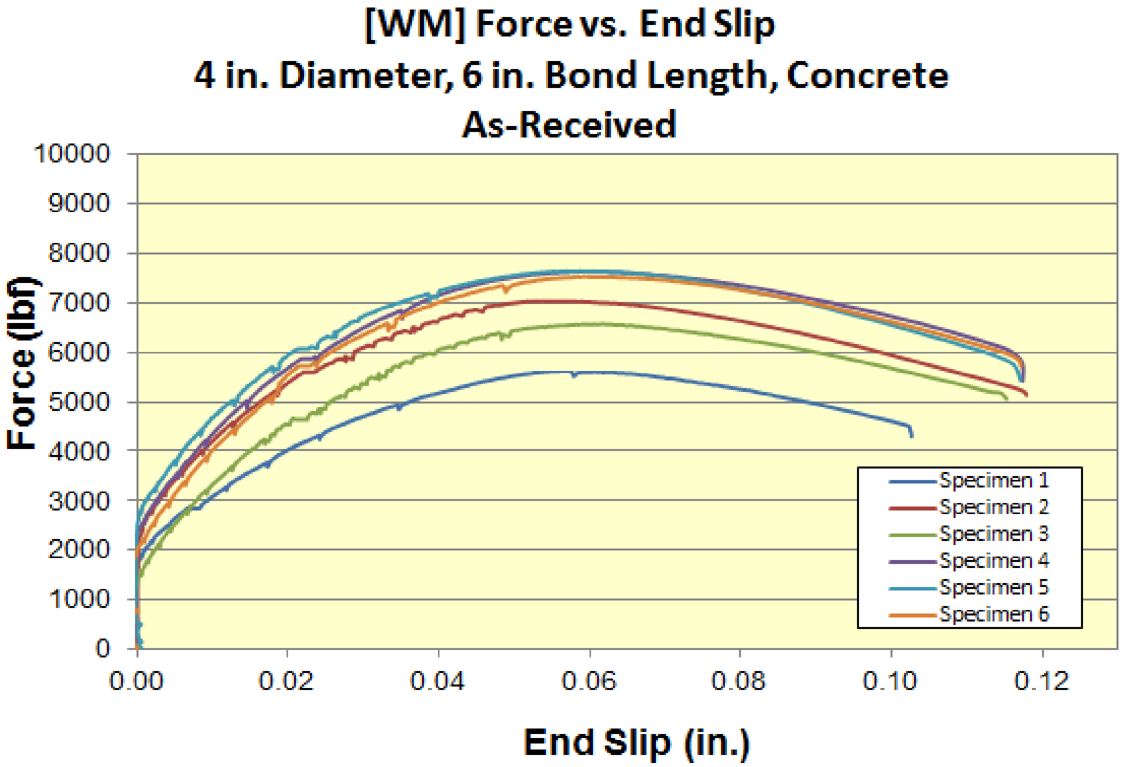


Figure N.12 As-received [WM] force vs. end slip individual graphs at CXT

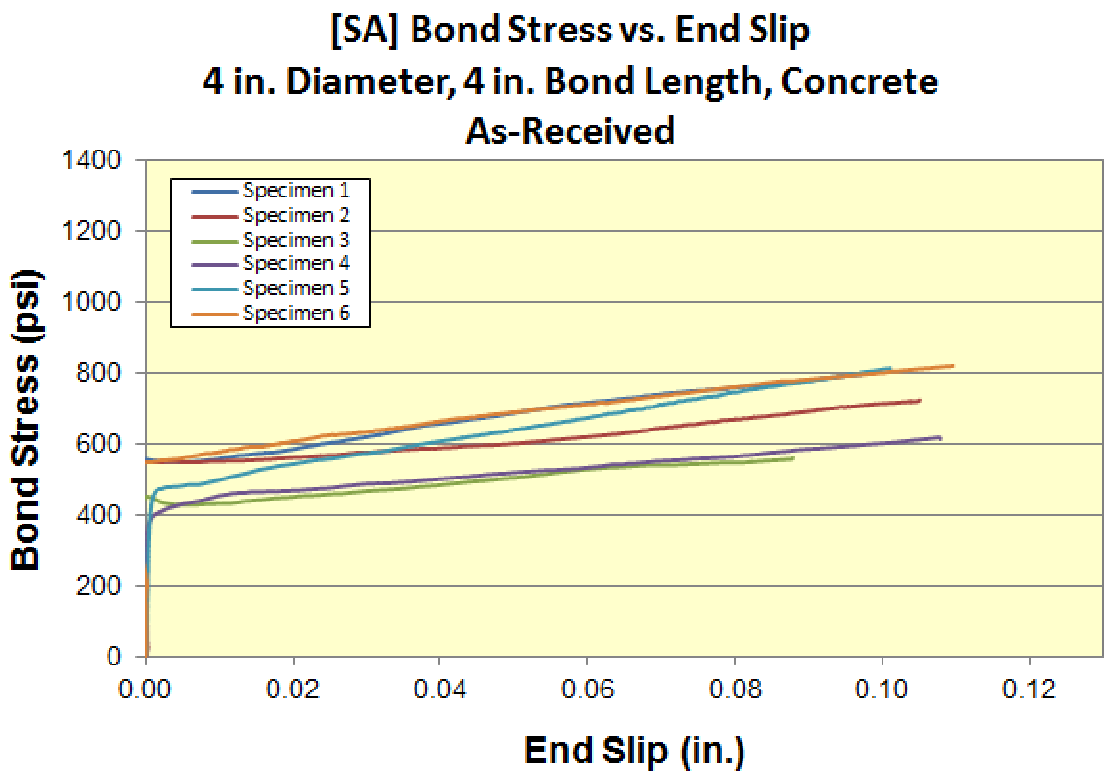


Figure N.13 As-received [SA] force vs. end slip individual graphs at CXT

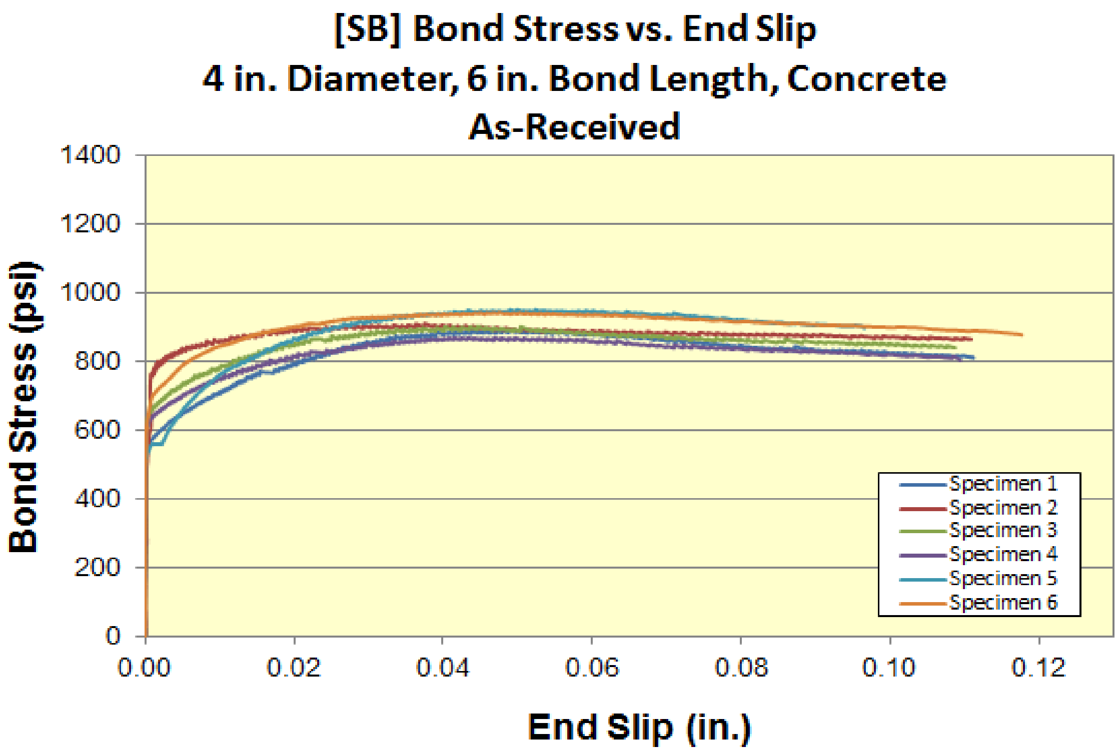


Figure N.14 As-received [SB] force vs. end slip individual graphs at CXT

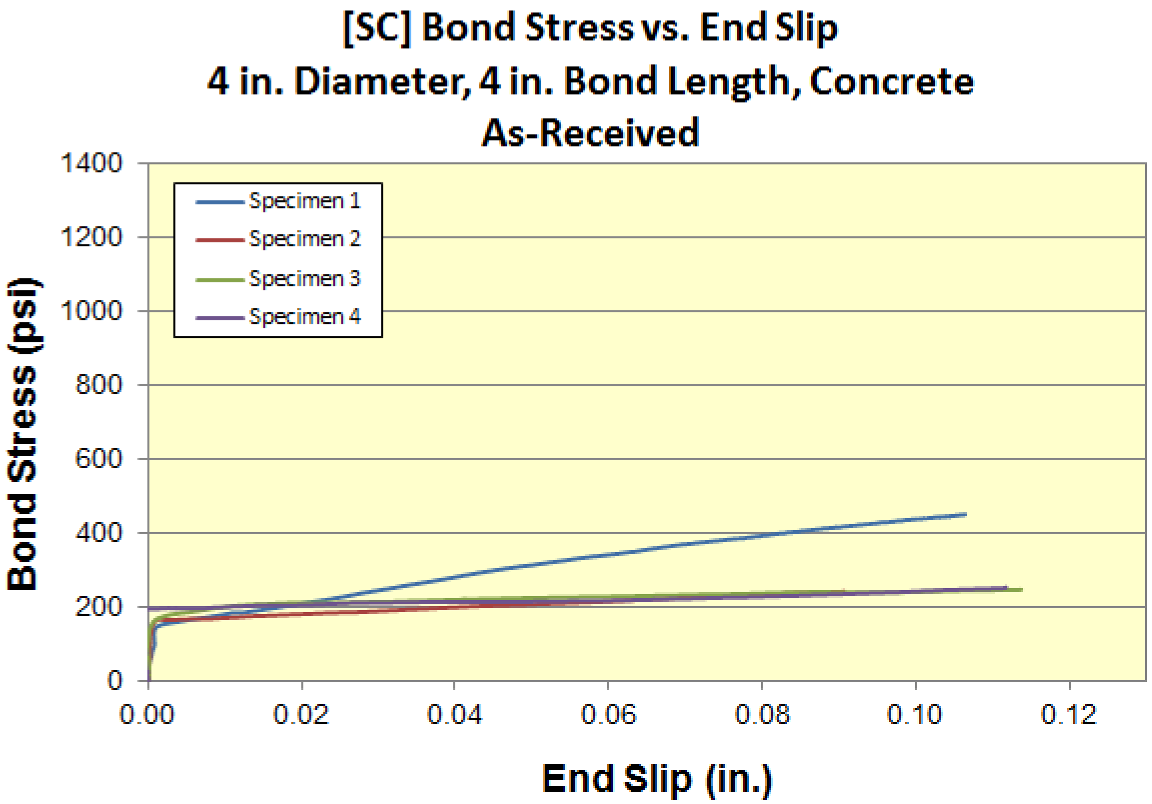


Figure N.15 As-received [SC] force vs. end slip individual graphs at CXT

Appendix O - Lab and Plant Phases; Individual Pullout Data Comparison

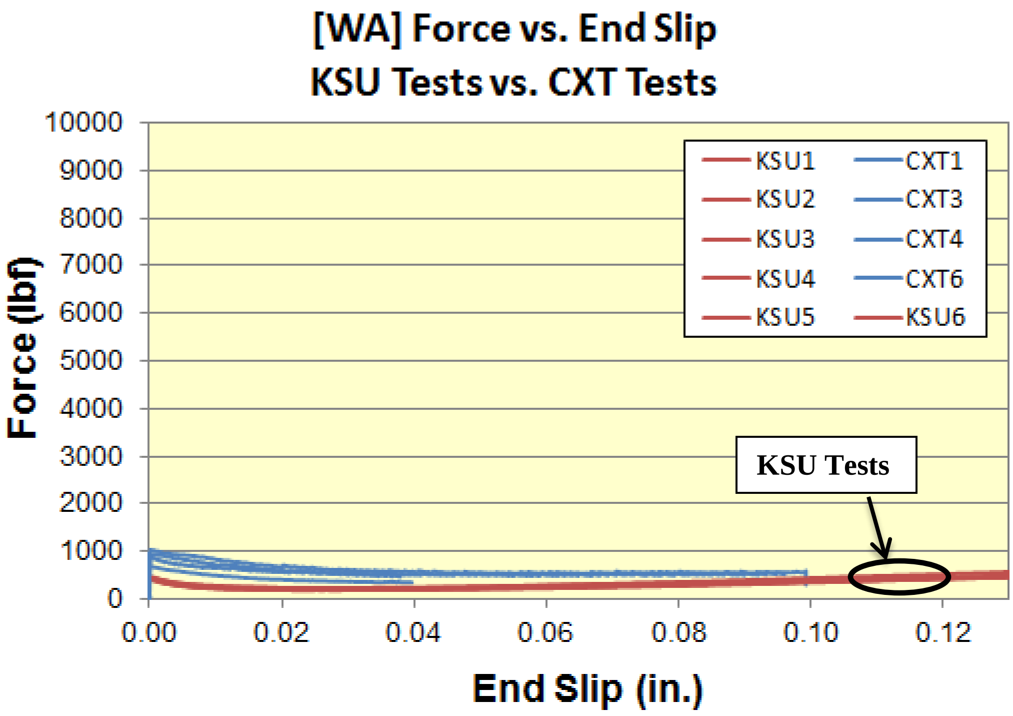


Figure O.1 [WA] force vs. end slip individual graphs, KSU vs. CXT

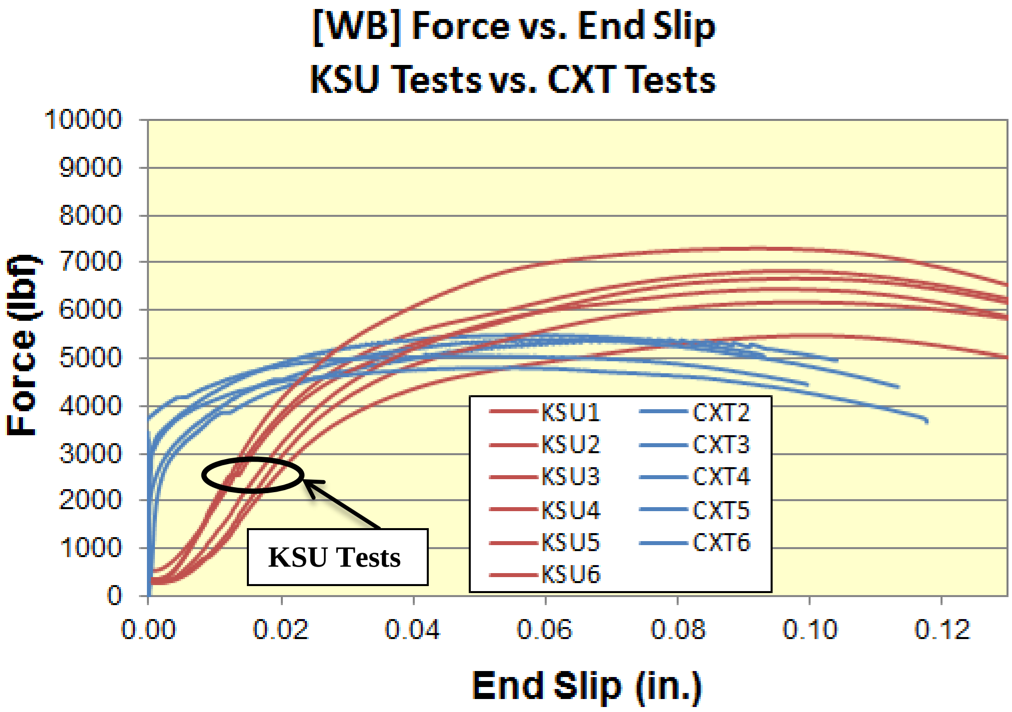


Figure O.2 [WB] force vs. end slip individual graphs, KSU vs. CXT

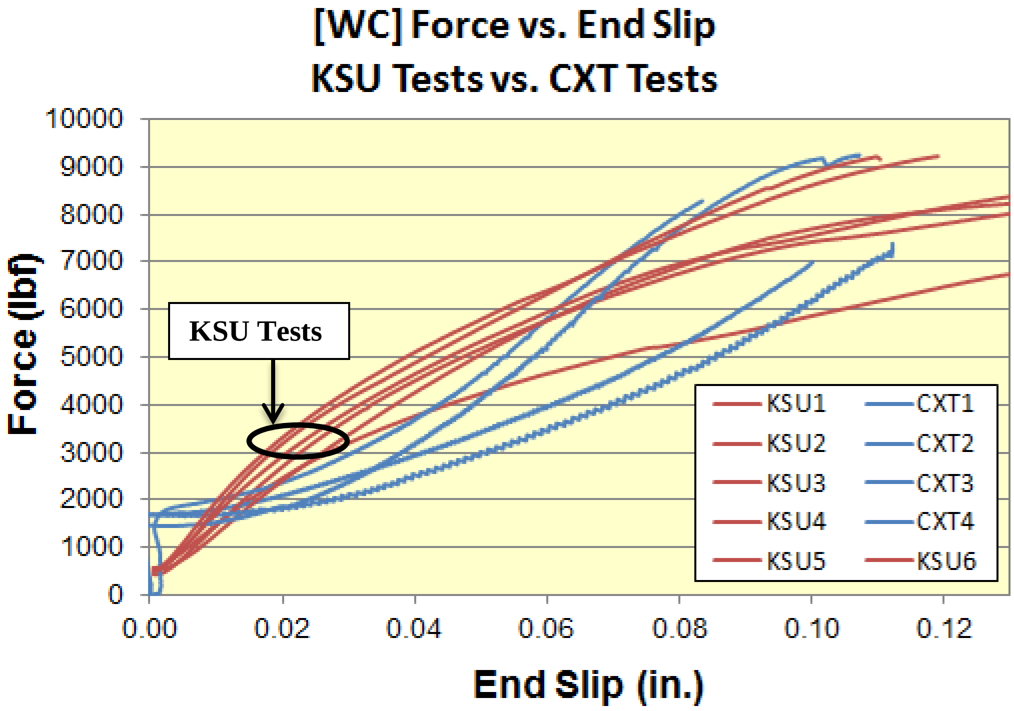


Figure O.3 [WC] force vs. end slip individual graphs, KSU vs. CXT

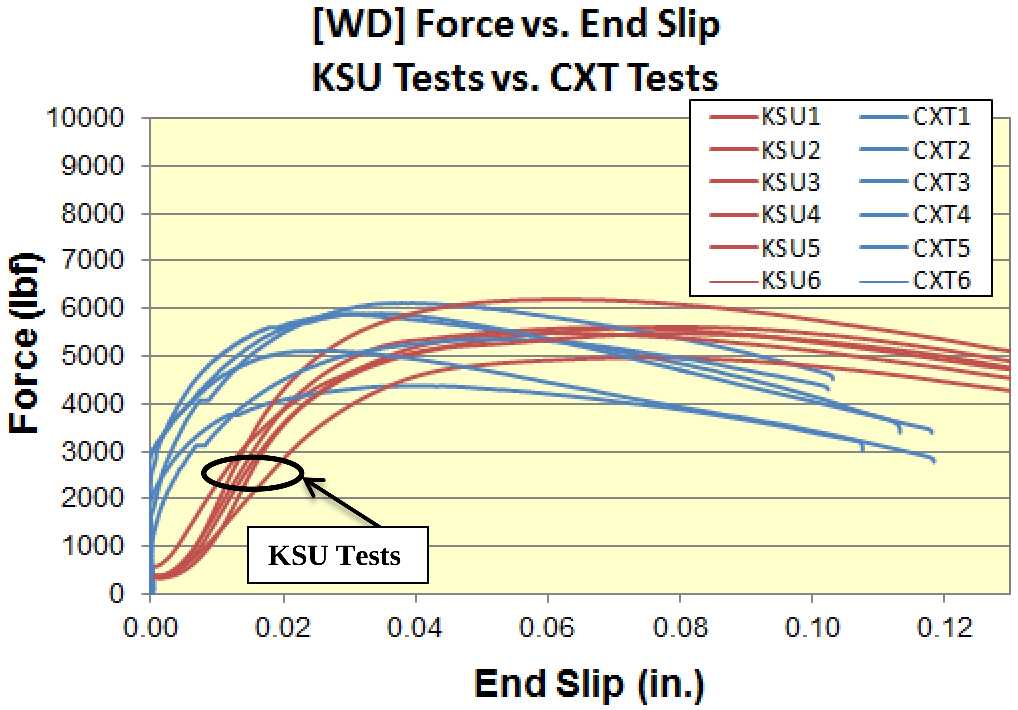


Figure O.4 [WD] force vs. end slip individual graphs, KSU vs. CXT

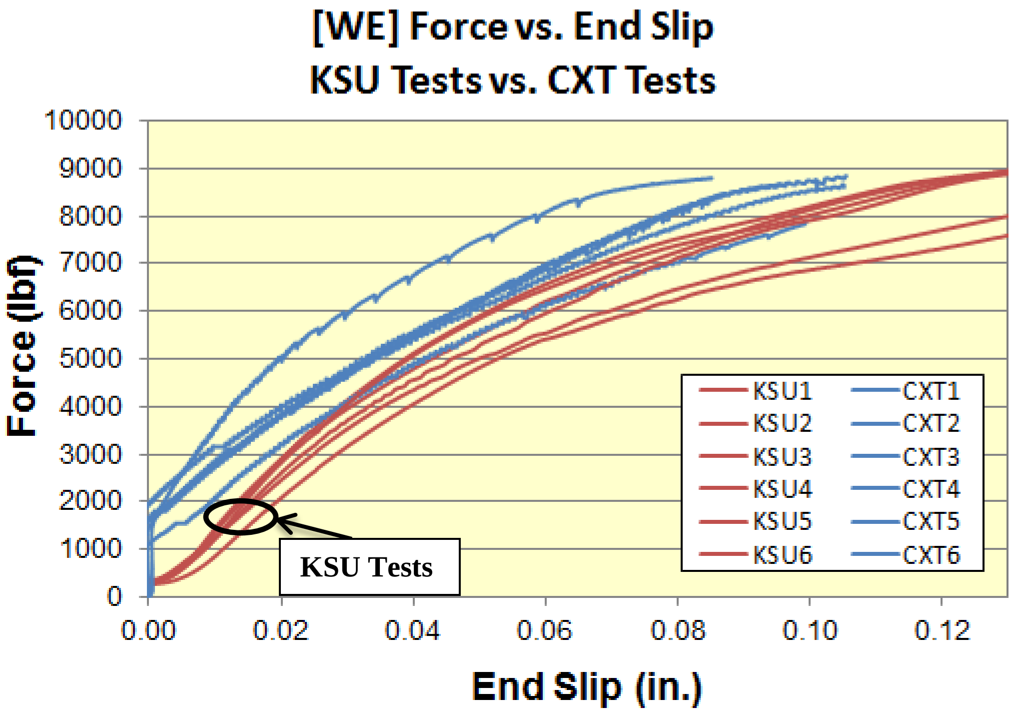


Figure O.5 [WE] force vs. end slip individual graphs, KSU vs. CXT

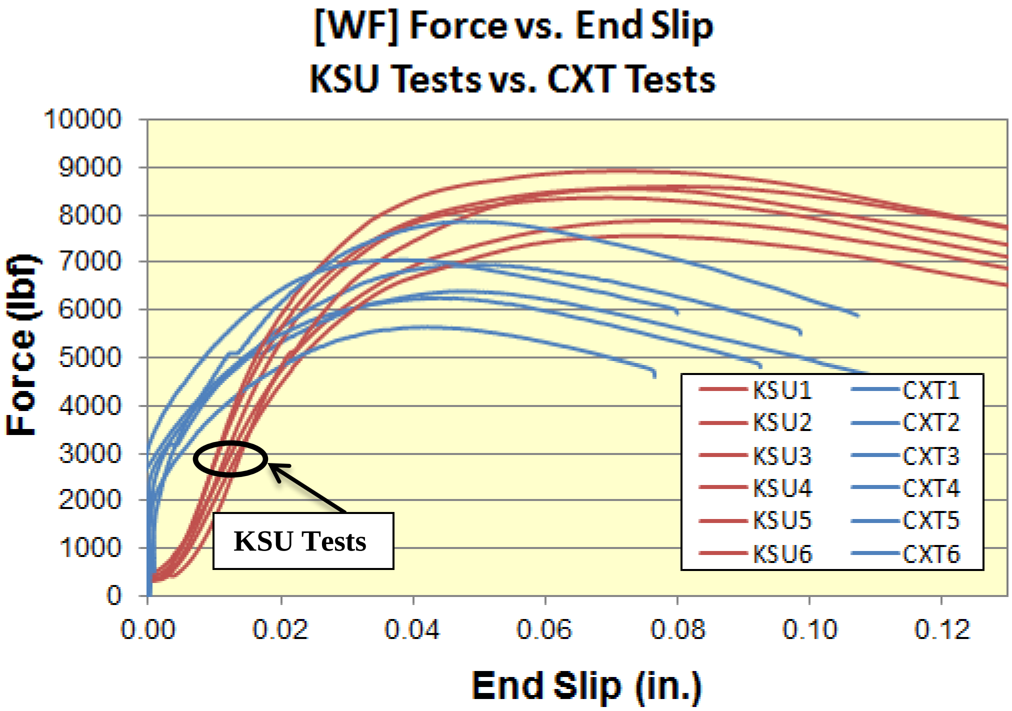


Figure O.6 [WF] force vs. end slip individual graphs, KSU vs. CXT

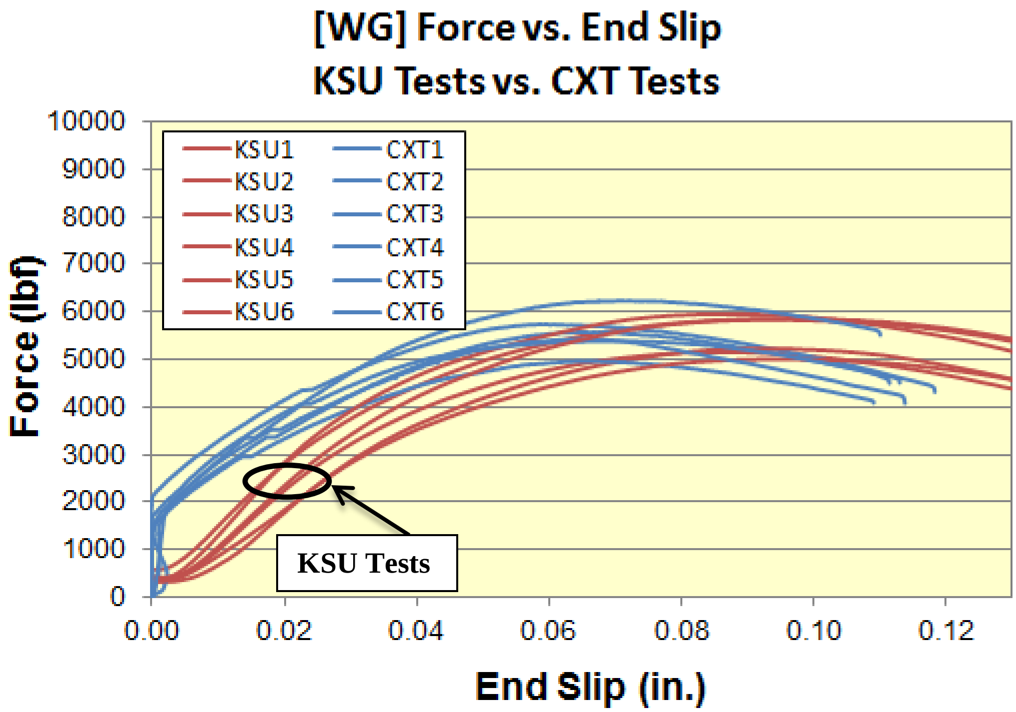


Figure O.7 [WG] force vs. end slip individual graphs, KSU vs. CXT

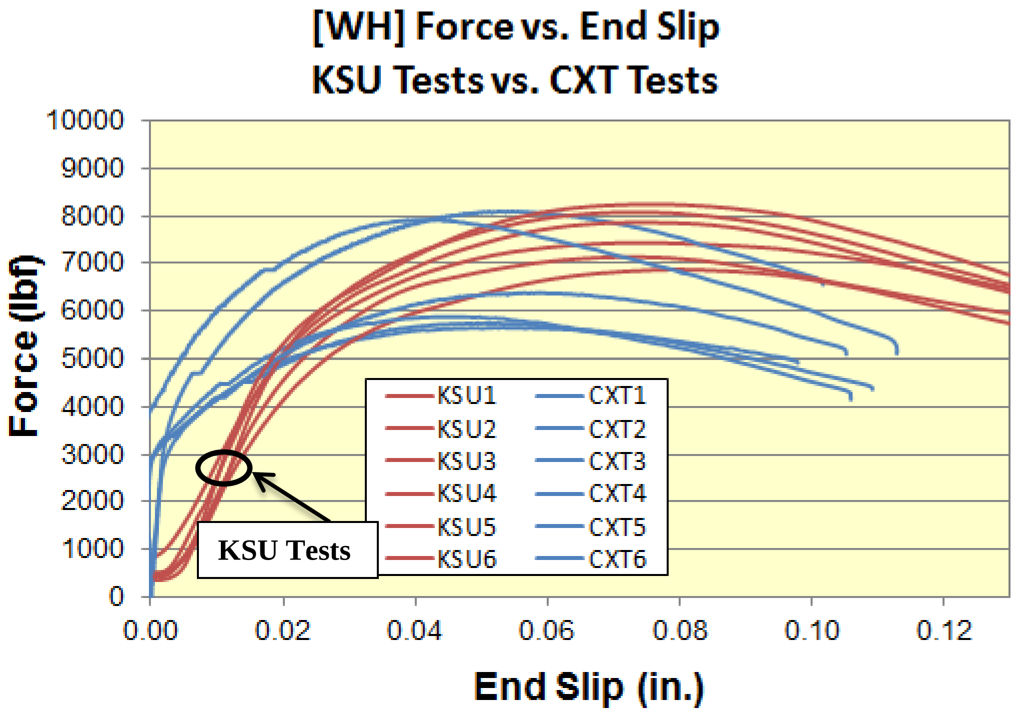


Figure O.8 [WH] force vs. end slip individual graphs, KSU vs. CXT

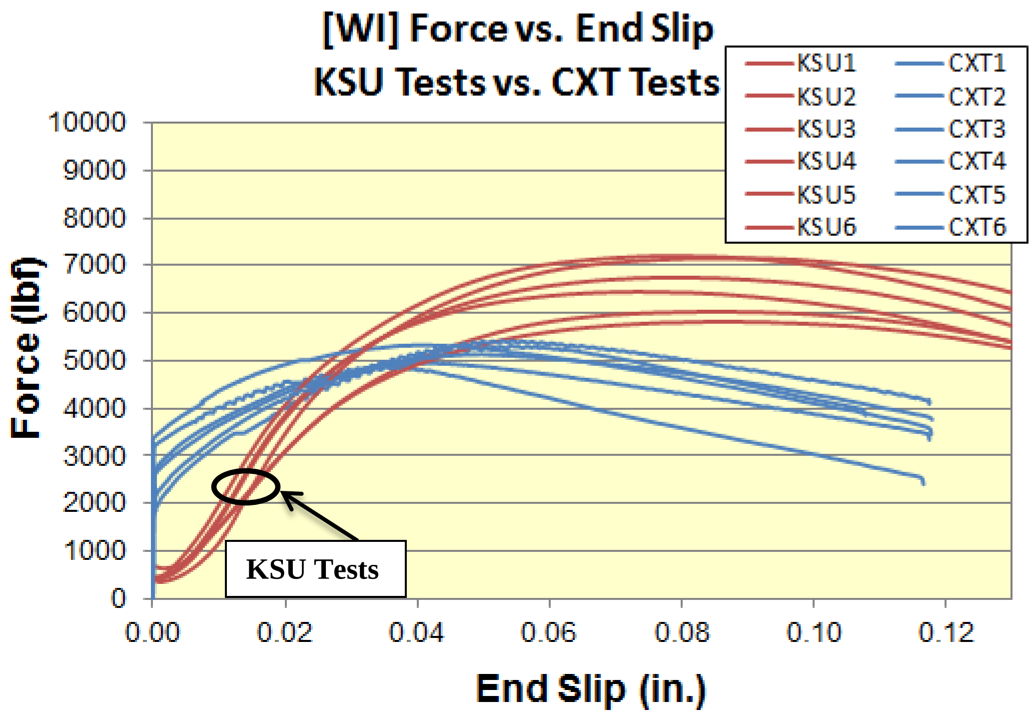


Figure O.9 [WI] force vs. end slip individual graphs, KSU vs. CXT

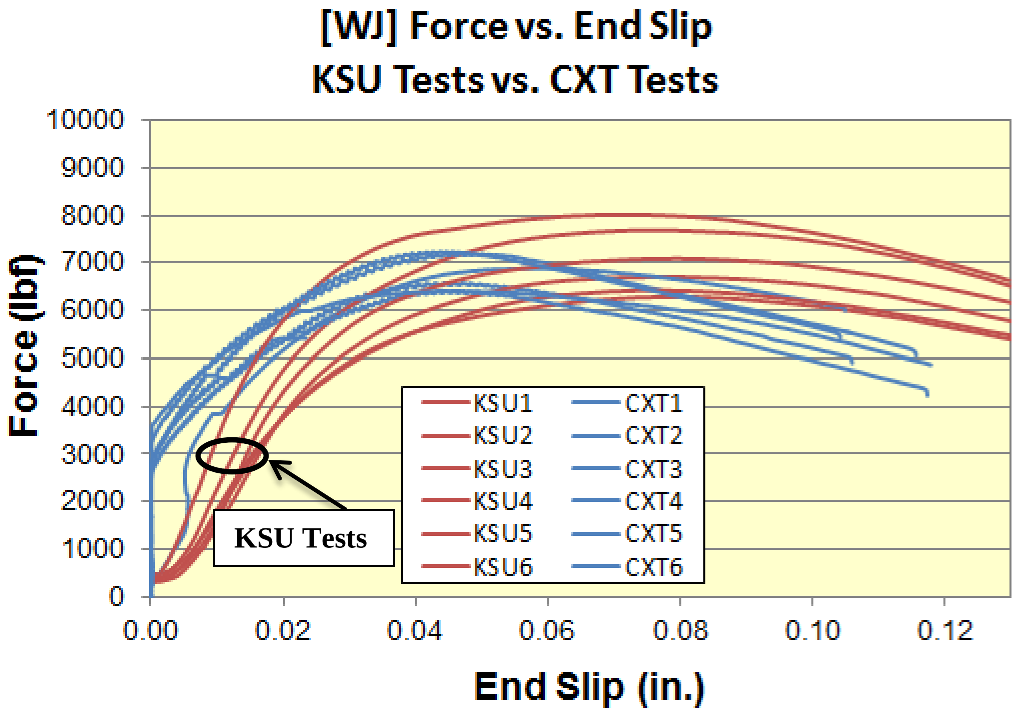


Figure O.10 [WJ] force vs. end slip individual graphs, KSU vs. CXT

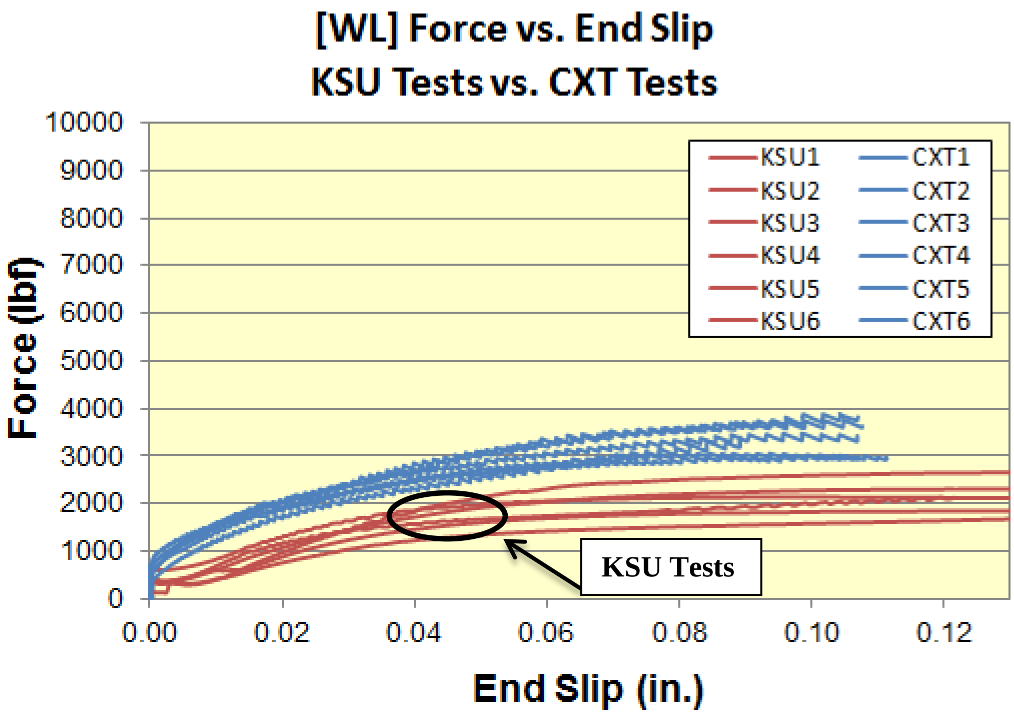


Figure O.11 [WL] force vs. end slip individual graphs, KSU vs. CXT

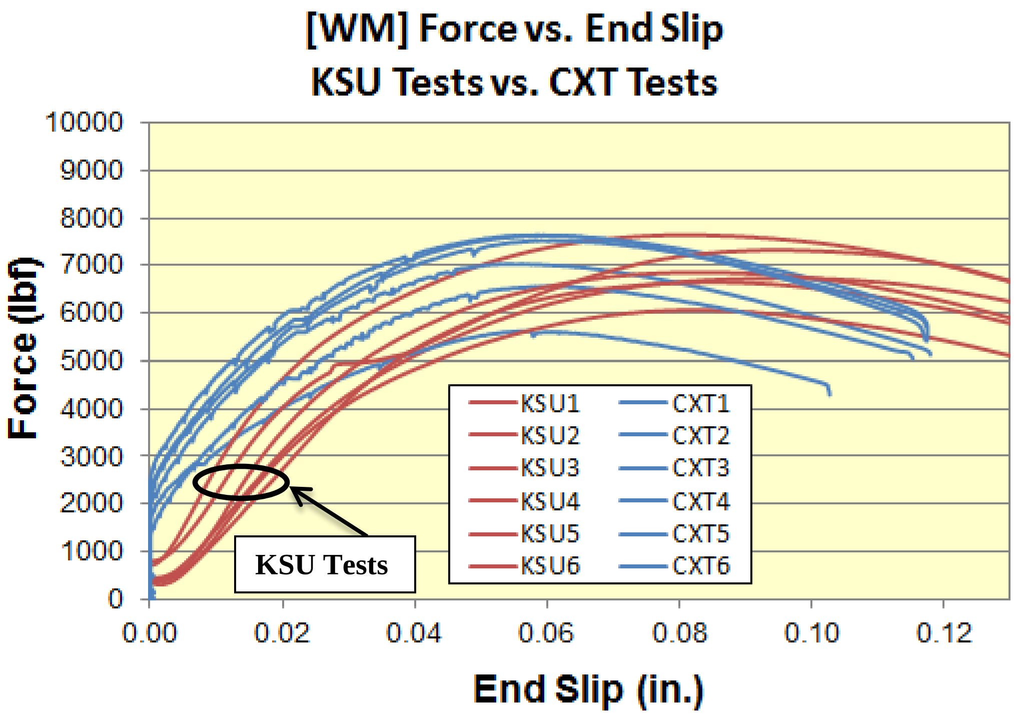


Figure O.12 [WM] force vs. end slip individual graphs, KSU vs. CXT

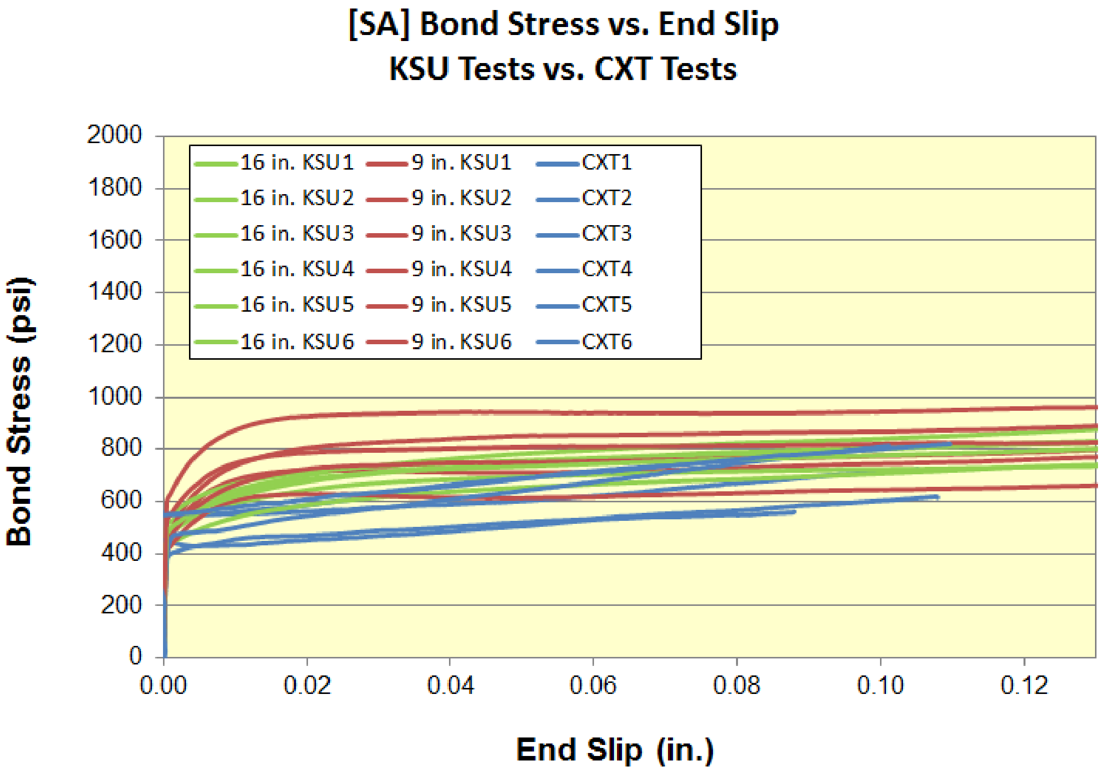


Figure O.13 [SA] force vs. end slip individual graphs, KSU vs. CXT

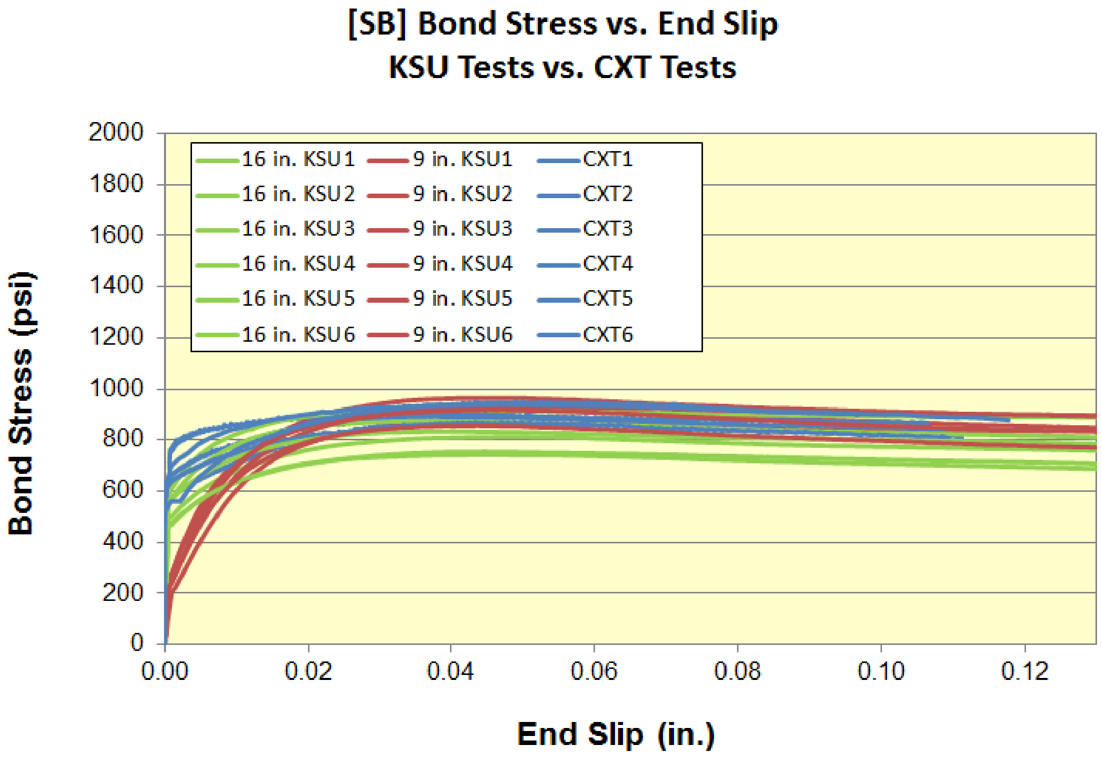


Figure O.14 [SB] force vs. end slip individual graphs, KSU vs. CXT

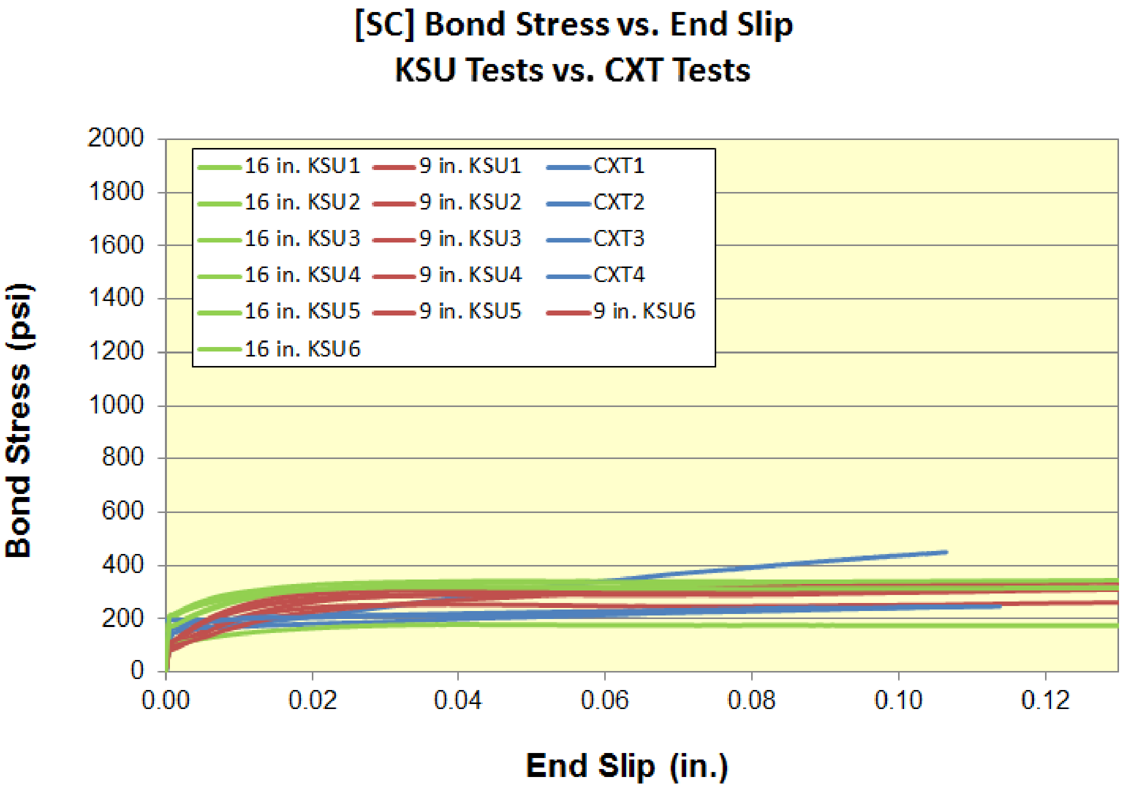
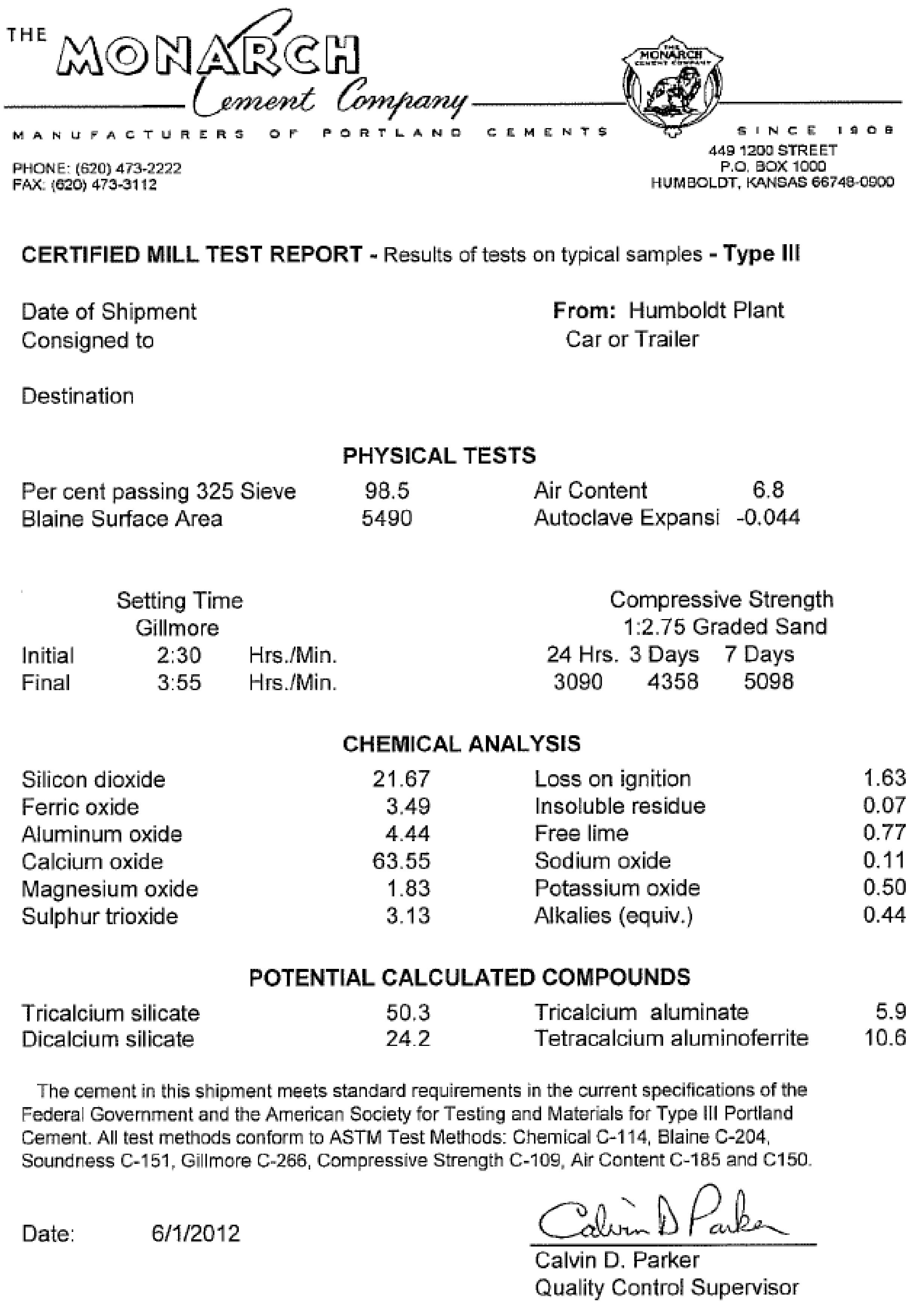


Figure O.15 [SC] force vs. end slip individual graphs, KSU vs. CXT

Appendix P - Mill Certification Tests for Cement Used in All Lab Pullout Tests



THE MONARCH
Cement Company
MANUFACTURERS OF PORTLAND CEMENTS
SINCE 1908
449 1200 STREET
P.O. BOX 1000
HUMBOLDT, KANSAS 66748-0900
PHONE: (620) 473-2222
FAX: (620) 473-3112

CERTIFIED MILL TEST REPORT - Results of tests on typical samples - **Type III**

Date of Shipment
Consigned to

From: Humboldt Plant
Car or Trailer

Destination

PHYSICAL TESTS

Per cent passing 325 Sieve	98.5	Air Content	6.8
Blaine Surface Area	5490	Autoclave Expansi	-0.044

	Setting Time Gillmore	
Initial	2:30	Hrs./Min.
Final	3:55	Hrs./Min.

Compressive Strength
1:2.75 Graded Sand

24 Hrs.	3 Days	7 Days
3090	4358	5098

CHEMICAL ANALYSIS

Silicon dioxide	21.67	Loss on ignition	1.63
Ferric oxide	3.49	Insoluble residue	0.07
Aluminum oxide	4.44	Free lime	0.77
Calcium oxide	63.55	Sodium oxide	0.11
Magnesium oxide	1.83	Potassium oxide	0.50
Sulphur trioxide	3.13	Alkalies (equiv.)	0.44

POTENTIAL CALCULATED COMPOUNDS

Tricalcium silicate	50.3	Tricalcium aluminate	5.9
Dicalcium silicate	24.2	Tetracalcium aluminoferrite	10.6

The cement in this shipment meets standard requirements in the current specifications of the Federal Government and the American Society for Testing and Materials for Type III Portland Cement. All test methods conform to ASTM Test Methods: Chemical C-114, Blaine C-204, Soundness C-151, Gillmore C-266, Compressive Strength C-109, Air Content C-185 and C150.

Date: 6/1/2012

Calvin D Parker
Calvin D. Parker
Quality Control Supervisor