INTERLABORATORY STUDY FOR ASTM A1081 STANDARD TEST METHOD FOR EVALUATING BOND OF SEVEN-WIRE STEEL PRESTRESSING STRAND

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ABSTRACT

ASTM A1081 Standard Test Method for Evaluating Bond of Seven-Wire Steel Prestressing Strand was developed to provide a simple index test for determining the strand bond characteristics of prestressing strand for acceptance and quality control. An interlaboratory study that included nine laboratories was performed to quantify the test method precision and bias, and provide information on challenges faced by laboratories in running the test. Strand from three sources was tested in the interlaboratory study using two different procedures. The first procedure was the test method as adopted by ASTM A1081. The second test method used was a modified version that requires the mortar flow fall in a narrower range of 105-120 instead of 100-125 as required in ASTM A1081, no time window for performing the test, and a prescribed water to cement ratio of 0.45. The results showed that the changes suggested to ASTM A1081 were able to reduce the coefficient of variation from 14.5 to 11%.

Keywords: Standard Test for Strand Bond, Precision, Bias.

INTRODUCTION

An interlaboratory study was conducted in order to investigate the precision and bias of the newly adopted ASTM A 1081 "Standard Test Method for Evaluating Bond of Seven-Wire Steel Prestressing Strand" [1]. This test method was developed in the 1990s and 2000s, during the four rounds of a research program led by Professor Bruce Russell at the University of Oklahoma and Oklahoma State University, and funded by the North American Strand Producers (NASP) Association. The NASP study's goal was to develop a simple and consistent test procedure that can quantify the bonding ability of seven-wire steel prestressing strand to cementitious materials [2], [3], [4], [5]. ASTM accepted the test procedure in 2012, but the precision and bias statement of the standard method has yet to be developed.

The bonding behavior of steel strand plays a very significant role in prestressed concrete; the transferring of tensile prestressing forces from the initially tensioned steel reinforcement to the cementitious material is achieved by the bonding action between the two materials. Since strands of identical grade and type have been found to vary in bonding performance [6], it is important to prequalify and monitor the bond quality of steel before relying on the bond to transfer prestressing forces to concrete sections.

The test method developed by Dr. Russell involves tensile loading of strand samples embedded into mortar filled steel cylinders, via a displacement controlled mechanism. The bonding capacity of a steel strand sample is measured as the applied tensile load, in pounds, that corresponds to a specified 0.1 inch displacement of the strand [1]. This testing procedure provides a simple method of testing the bonding characteristics of prestressing strand in a laboratory without having to construct large scale concrete specimens. Even though the cementitious material used in this case is mortar instead of concrete, the test method has been correlated to the performance of full scale concrete applications [4].

Prior to the development of this method, prestressing strand bonding capacities were tested using the Moustafa pullout test method, which involved un-tensioned strand samples embedded 18 in vertically in large concrete blocks. This pullout test method was originally developed in 1974 at Concrete Technology Corporation (CTC) in Tacoma, Washington, by Saad Moustafa [6]. During the first round of the NASP study [2], the Moustafa pullout test method along with two other forms of strand pullout tests were investigated and compared by Dr. Russell in order to determine the most consistent and reliable testing procedure for the bonding behavior of steel prestressing strand. A modified version of ASTM A981, also named the PTI test [7], was tested in that study and involves testing strand samples embedded in grout. The Friction Bond pullout test was also tested by Dr. Russell during the first round of the NASP study [2]. In the Friction Bond pullout test, the mechanical splicing of bare strands was investigated.

The current ASTM A1081 test method was developed during the second, third and fourth rounds of the NASP study [3], [4], [5], due to inability of the initially investigated pullout test methods to predict the bonding behavior of prestressing steel strands reliably and consistently [2]. The test method was called the NASP bond test during the development tests by Dr. Russell, and it follows the same procedures as ASTM A981, which is the Standard Test Method for evaluating Bond Strength of 0.6-in. Diameter Steel Prestressing Strand, Grade 270, Uncoated, Used in Prestressed Ground Anchors. The only difference between the two procedures is that instead of using cement grout as specified in the procedure of ASTM A981, the new method was formatted to test strand samples embedded in mortar [3].

During the second round of the NASP Strand Bond Testing study, the Moustafa test, the ASTM A981/PTI pullout test along with the NASP test were investigated. The PTI test or ASTM A981 specifies that the outcome of the procedure should be the pullout force in lb that a strand sample requires in order to be displaced by 0.01 in. from its original position. During the NASP study, and for both the cases of the PTI or ASTM A981 as well as the developing NASP test procedure, force readings were taken at a 0.01 in. displacement as well as 0.1 in. displacement of the free end of each strand sample. Both test methods experienced lower variability when the readings were taken at 0.1 in. instead of 0.01 in. It was also noted that the NASP test produced less variable test results when compared to either the Moustafa test or the ASTM A981 / PTI Test method [3]. During the three rounds of the NASP Strand Bond Testing Study, it was shown that the NASP pullout test was a more repeatable method than both the Moustafa test and PTI test. The developing method also displayed greater correlation with the transfer lengths measured during the third round of the NASP study than the other methods tested, where rectangular beam sections prestressed with one or two strands were tested [4]. The NASP test method was therefore recommended by Dr. Russell to be adopted as the standard procedure for evaluating the bond of seven-wire steel prestressing strand [5].

The Precast/Prestressed Concrete Institute (PCI) hired Professors Hawkins and Ramirez to conduct a due diligence review of the test procedure, who recommended additional examination of the method [8]. The main concern was over the lack of an enforceable minimum pullout value threshold required to produce reliable bond. A round robin study with the purpose of determining the reproducibility of the test results was recommended before attempting to establish a threshold value for the test method [8].

An interlaboratory study of ASTM A1081 “Standard Test Method for Evaluating Bond of Seven-Wire Steel Prestressing Strand” [1] was led by Kansas State University (KSU). A ruggedness study of the pullout test method was conducted first, where the researchers investigated the effects of varying the test loading rate, mortar compressive strength, and mortar mixture flow of the samples [9].

After evaluating the findings of the ruggedness testing study and observations while altering different variables of the test method and studying the related effects, KSU researchers defined a modified ASTM A1081 pullout test procedure which was incorporated in the interlaboratory study, along with the standard test method as specified by ASTM. This paper documents the results of the interlaboratory study performed to quantify the precision and bias of ASTM A1081.

METHODS

Two methods of testing strand bond were performed during the round robin study investigating the “Standard Test Method for Evaluating Bond of Seven-Wire Steel Prestressing Strand”, designated ASTM A1081. The first method, called hereafter Method A, recommends testing strand samples exactly as prescribed by the ASTM standard. A second method was defined by the project investigators, hereafter called Method B, which was also a version of the standard ASTM A1081 test method, modified to reduce variability based on the ruggedness test results.

The standard ASTM A1081 test method specifies that samples be tested at 24 ± 2 hours after mortar mixing takes place [1]. The test also requires that the mortar mixture compressive strength of the samples be between 4500 and 5000 psi at the time of testing [1]. No requirements are imposed on mixture proportioning by the ASTM standard as long as the flow and mortar strength requirements are met [1]. The standard test method allows for a range of mortar flow between 100-125 % [1], as determined by ASTM C1437 [10].

For Method B, a water-cement ratio (w/c) of 0.45 was specified. Because different cements would give different strength gain rates at a constant w/c, the time window requirement was deleted for Method B. Because the ruggedness study determined that mortar flow was a significant variable in bond testing, this requirement was modified for Method B. The mortar mixture flow allowable range for Method B was tightened to 105-120 % [9]. A specific, uniformly graded sand source was required for Method B, in order to reduce the mortar mixture flow variability, which was found to be a significant factor during the ruggedness study previously conducted at KSU [9]. Table 1 shows a comparison of the key specification differences between Method A (ASTM A 1081) and Method B.

Table 1 Method A and Method B Specifications

	Method A	Method B
Time of test	24 ± 2 hours after mixing	No constraint
w/c ratio	No constraint	0.45
Mortar mixture flow	100-125 %	105-120 %
Compressive Strength at time of test	4500-5000 psi	4500-5000 psi
Sand Source	ASTM C33 sand	Dolese sand, specified gradations
Cement Source	ASTM C 150 type III cement	ASTM C 150 type III cement

In the case of Method B, the project investigators omitted the requirement of keeping the tests within the time frame of 24 ± 2 hours, and required only that the mortar mixture compressive strength is kept between 4500 and 5000 psi. The time window requirement was omitted after initial testing revealed that it was not possible for all 5 cement source mixtures used at KSU to reach the specified compressive strength of 4500-5000 psi within 22-26 hours from mixing time at the Method B specified water-cement ratio (w/c) of 0.45.

After the test method specifications were finalized, a webinar was shared with the participating laboratories, where they were guided on testing procedures and general test setup since most of the participating laboratories had not previously run this test as a first step in preparing for the Interlaboratory study. A detailed guide was sent to all participating laboratories in order to assist with their mixture development process; however laboratories were not required to follow this mixture development process as long as the mortar mixtures they developed met the test requirements. Once a participating laboratory had successfully developed their trial mixtures for Method A and Method B, a researcher from KSU traveled to each laboratory to observe testing and record data.

MATERIALS

ASTM A1081 allows any ASTM C33 sand source and any ASTM C150 type III cement source to be used when designing the mortar mixture [1]. There was some concern that the sand gradation, hardness, and angularity could affect the test results. To eliminate this concern, Method B required the use of a specific source of sand at a specified gradation for all testing laboratories. The sand source utilized for the Method B mortar mixtures was supplied by Dolese Brothers Co, Oklahoma, the suppliers of the sand utilized during the NASP study, where the standard test method was developed. The sand was sieved by KSU and sent to the participating research labs for Method B testing. The sand gradations used for all Method B mixtures are shown in Table 2 [9].

Table 2 Sand Gradations [9]

Sieve	% Total	% Passing
#4	0.5	99.5
#8	4.8	94.7
#16	15.9	78.8
#30	33.5	45.3
#50	31.8	13.5
#100	12	1.5
#200	1.5	0.0

The requirements regarding the cement source were kept as specified by the ASTM standard for Method B also, allowing the use of any ASTM C150 Type III cement source [11].

This study was conducted using 0.5 inch diameter, seven-wire steel strand samples that were supplied by three different manufacturers. The strands used in this study were all designated as 270 ksi minimum ultimate tensile strength, low relaxation; uncoated steel strands meeting ASTM A416 [12].

Initially the project investigators tested strand samples that came from eight strand manufacturing plants, following the procedures specified in ASTM A1081 method, and selected the three samples since they tested into the pullout force categories that were originally set. The three pullout force categories were selected in order to accommodate the final project goal which is to set an acceptance minimum threshold for 0.5 inch diameter seven-wire steel prestressing steel strand bond that will ensure meeting code requirements for transfer and development length. The three strands that were selected fall in the lower bonding category of prestressing strand sources. Not all of the sources tested were market place strand. Strand I was not a marketplace strand and was selected for this study in order to provide a low bonding source. Figure 1 [9] shows the pullout force values for the eight strand source samples that were tested during the initial strand selection process. The chart presents each of the 6 strand specimens tested per source, since ASTM A1081 specifies that the official test result is the average value of 6 individual strand specimens.

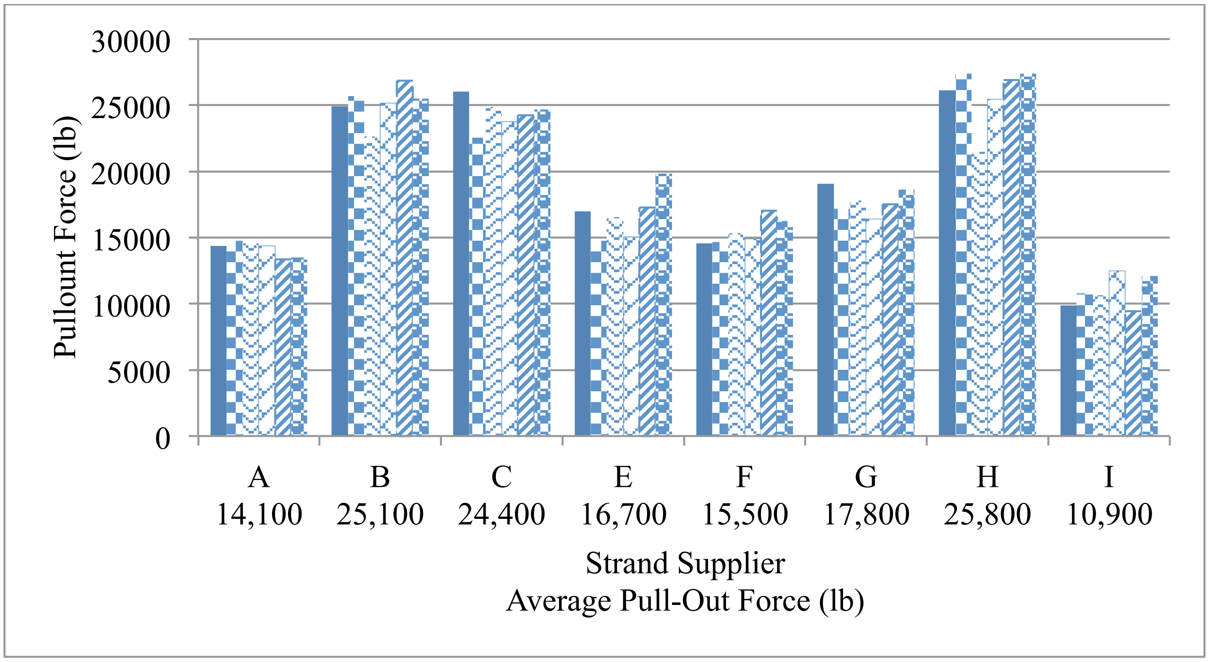

Figure 1 Pullout Force for Six specimens Tested per Strand Source (lb) [9]

The final three samples that were selected to participate in the research program were labeled Strand A, Strand G, and Strand I. Strand coils of at least 3000 feet length were supplied to KSU laboratories by the three strand manufacturers whose strand samples were selected during the initial selection round. Additional testing followed and the pullout force values for the three strand sources were confirmed. For the Interlaboratory study, strand samples were cut by KSU personnel, labeled and shipped to all participating laboratories.

The three strands were initially tested at KSU Civil Engineering laboratories, using a simple mixture proportioning method developed to quickly design a mortar mixture made with a specific cement source that will meet ASTM A1081 requirements and described elsewhere

[13]. The mixture characteristics for the 5 mortar mixtures developed using the different cement sources available at KSU are summarized in table 3.

Table 3 Mixture Proportions and Mixture Flow for Mortar Samples Made with 5 Different Cement Sources

	Water to cement (w/c)	Sand to cement (s/c)	Mixture flow (%)
cement 1	0.455	2.60	123
cement 2	0.480	2.00	121
cement 3	0.475	2.85	124
cement 4	0.450	2.50	123
cement 5	0.452	2.50	123

An average maximum difference of over 21% was obtained when comparing the pullout test results of identical strand sources tested in mortar mixtures that meet ASTM A 1081 standards but utilized different ASTM C 150 type III cement sources. The actual test results per strand source and cement source are listed in table 4.

Table 4 Average Test Results from KSU labs per Strand, per Cement Source using ASTM A1081 standard method

	Strand A	Strand G	Strand I
cement 1	12,800 lb	17,400 lb	11,500 lb
cement 2	13,500 lb	17,500 lb	11,300 lb
cement 3	15,300 lb	20,500 lb	11,900 lb
cement 4	16,600 lb	20,900 lb	11,700 lb
cement 5	15,700 lb	21,500 lb	13,400 lb
Max. Difference	23%	24 %	17%

The work proceeded with testing the three strands in 5 additional mortar mixtures which were prepared with the same 5 cements, but this time the water to cement ratio was kept consistent, at 0.45, for all 5 mixtures according to the Method B specifications. In this case, some of the mortar mixtures did not meet the test time specification set by ASTM A1081, but all samples were tested while their mortar compressive strength was between the specified range of 4500-5000 psi, ignoring the specified test time window. The results per strand and also per cement are listed in Table 5.

Table 5 Average Test Results from KSU Labs per Strand, per Cement Source Using w/c of 0.45 for All Mixtures

	Strand A	Strand G	Strand I
cement 1	14,300 lb	17,000 lb	11,600 lb
cement 2	14,900 lb	17,300 lb	13,000 lb
cement 3	13,400 lb	17,000 lb	11,000 lb
cement 4	13,500 lb	16,800 lb	10,400 lb
cement 5	15,300 lb	17,500 lb	11,200 lb
Max. Difference	14 %	4%	25%

Using a consistent w/c for all 5 cement mortar mixtures reduced the variability of the pullout test results down to an average maximum difference of just over 14%. It was decided to further investigate eliminating the test time window requirement and instead impose a set w/c of 0.45 to the standard ASTM A1081 test method. Considering this finding, Method B was included as an alternate method in the Interlaboratory study to determine if these modifications could reduce the test variability.

At Kansas State University, mortar mixtures were developed using the uniform sand supplied by Dolese Brothers Co, Oklahoma, which was oven dried, sieved and graded for every mixture, in order to reduce variability due to inconsistent moisture content and sand gradation. This sand was sieved and supplied by KSU to the participating laboratories for testing the strand bond using Method B.

RESULTS AND DISCUSSION

The average mortar compressive strength of each sample, mortar mixture flow, sample curing conditions, testing conditions, and pullout test results were gathered from 8 external participating laboratories during the months of the Interlaboratory study. Data from the 5 cement mixtures tested at KSU laboratories were included in the study, to total 13 sets of data, but since not all of the specifications were met by 2 of the external participating laboratories, their data was not taken into consideration during the final round of analysis, and therefore will not be presented in the data summary tables in this report.

The average mortar compressive strength during testing, average mortar mixture flow, and average pullout force per strand group from the remaining 6 laboratories and also from the 5 sets of data obtained by KSU labs are summarized in Table 6 for Method A, and Table 7 for Method B.

Table 6 Interlaboratory Study Data-Method A (ASTM A1081)

	Average Mortar Compressive Strength before test (psi)	Average Mortar Compressive Strength after test (psi)	Average Mortar Mixture Flow (%)	Strand A Average Pullout Force (lb)	Strand I Average Pullout Force (lb)	Strand G Average Pullout Force (lb)
KSU 1	4554	4701	122.5	12803	14739	16921
KSU 2	4655	4762	122.4	13534	11446	17534
KSU 3	4589	4736	118	15250	12036	20548
KSU 4	4654	4675	124	16564	11652	20423
KSU 5	4619	4641	122	15711	13441	21503
LAB 1	4630	4785	115	14163	10114	20725
LAB 2	4535	4668	120	10947	10515	16722
LAB 3	4634	4814	117.5	14634	12681	17127
LAB 4	4630	4995	111	11103	10682	13832
LAB 5	4699	4896	120.7	10687	8966	12715
LAB 6	4511	4522	123.5	13201	10955	16695

Table 7 Interlaboratory Study Data-Method B (modified ASTM A1081)

	Average Mortar Compressive Strength before test (psi)	Average Mortar Compressive Strength after test (psi)	Average Mortar Mixture Flow (%)	Strand A Average Pullout Force (lb)	Strand I Average Pullout Force (lb)	Strand G Average Pullout Force (lb)
KSU 1	4525	4485	114.5	14267	11585	17060
KSU 2	4525	4443	112	14890	12981	17307
KSU 3	4516	4731	116	13510	10373	16807
KSU 4	4579	4728	112.7	15343	11163	17495
KSU 5	4578	4794	116	13397	11027	16993
LAB 1	4648	4709	116	15250	9581	19037
LAB 2	4707	4884	113.5	13437	10331	20570
LAB 3	4551	4799	107.5	19367	13876	20591
LAB 4	4475	4820	115	12653	12445	17338
LAB 5	4359	4475	115.3	11886	10582	15046
LAB 6	4010	4115	114.5	13813	11589	17735

The mortar compressive strengths from Lab 6 during Method B tests were lower than expected because some of the mortar cubes tested had visible bugholes on the surface, indicating poor consolidation. The pullout tests were still performed as some of the cubes indicated adequate strength and the time from casting was similar to that seen for companion mixtures made with the same materials and proportions. The pullout test results from the interlaboratory study are illustrated in figures 2-7 in a more detailed representation that includes the high and low values for each group of 6 specimens tested. Each figure illustrates the pullout test values obtained per strand group, per method of testing, by the 8 external laboratories that participated in the study, and the 5 sets of data obtained by KSU labs utilizing a different cement source per set of data. The minimum and maximum pullout force values of the six strand samples tested per laboratory are shown in each chart. This also illustrates the range of values obtained by each laboratory, highlighting the variability of data within a single test site.

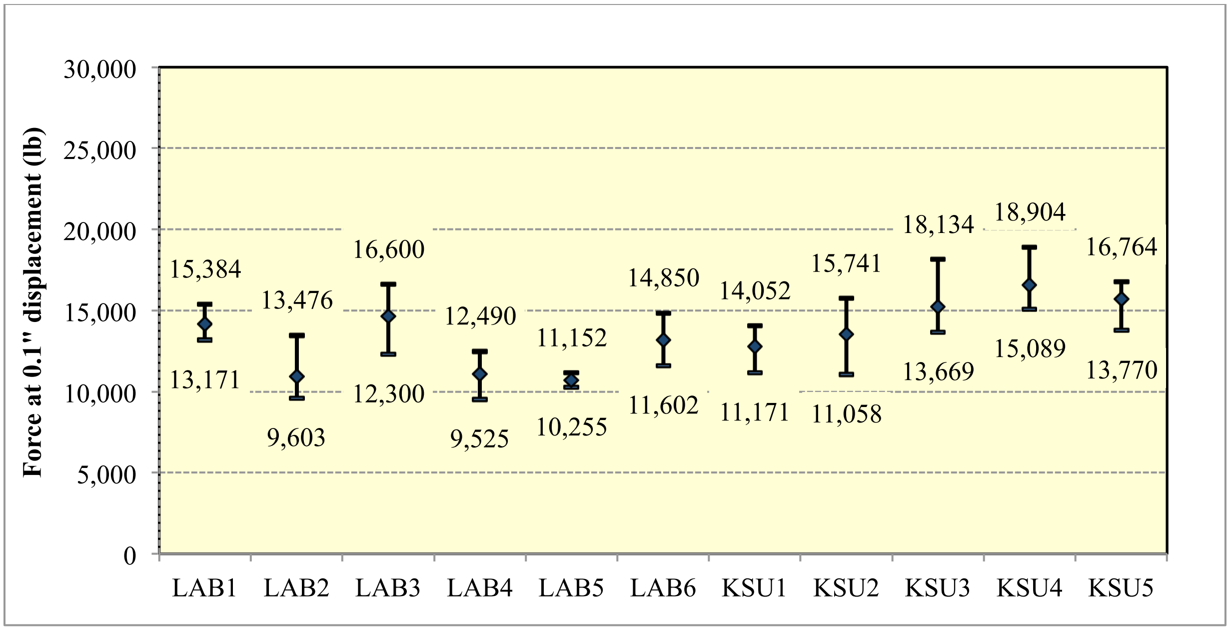

Figure 2 Interlaboratory Study Results, Method A- Strand A

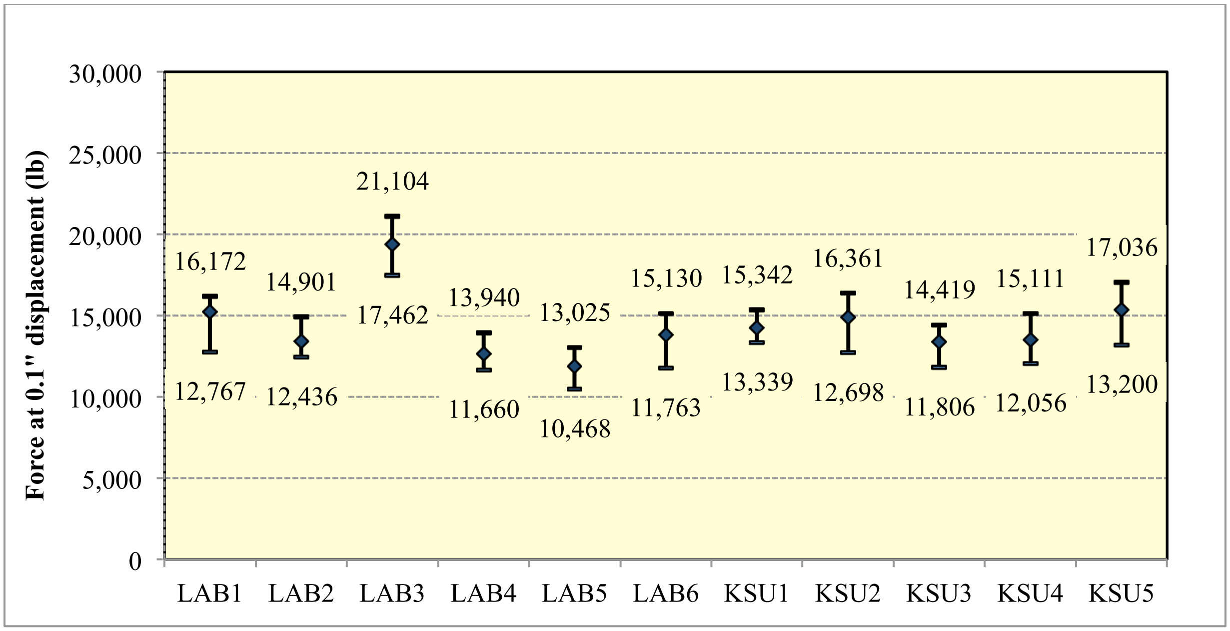

Figure 3 Interlaboratory Study Results, Method B- Strand A

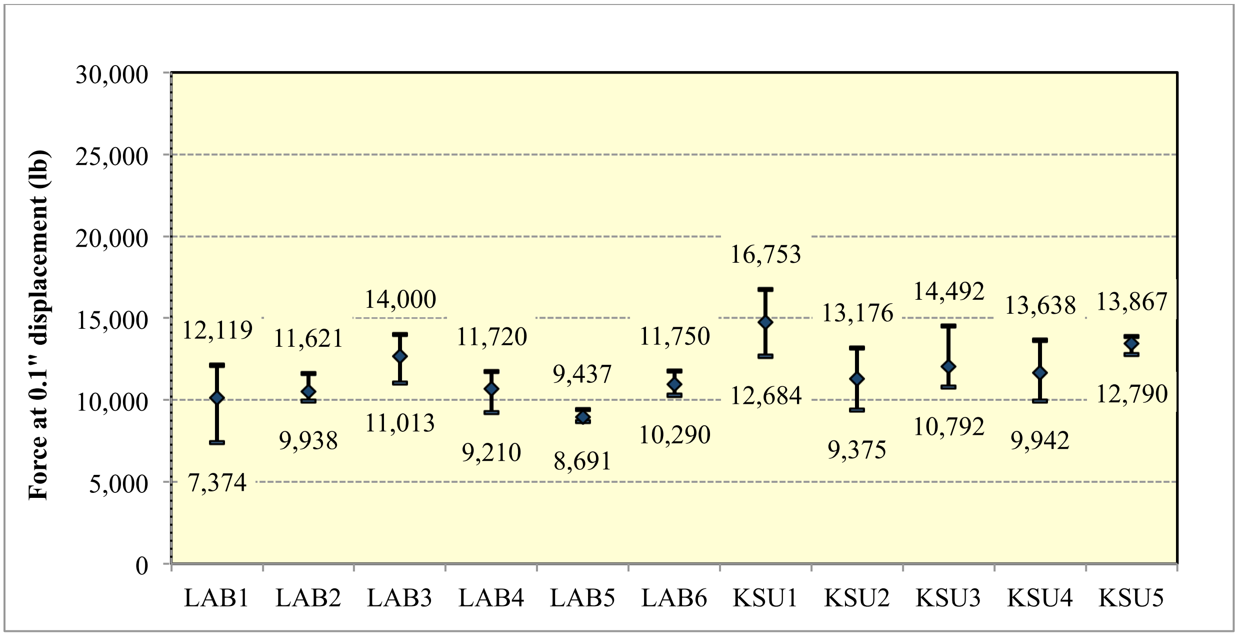

Figure 4 Interlaboratory Study Results, Method A- Strand I

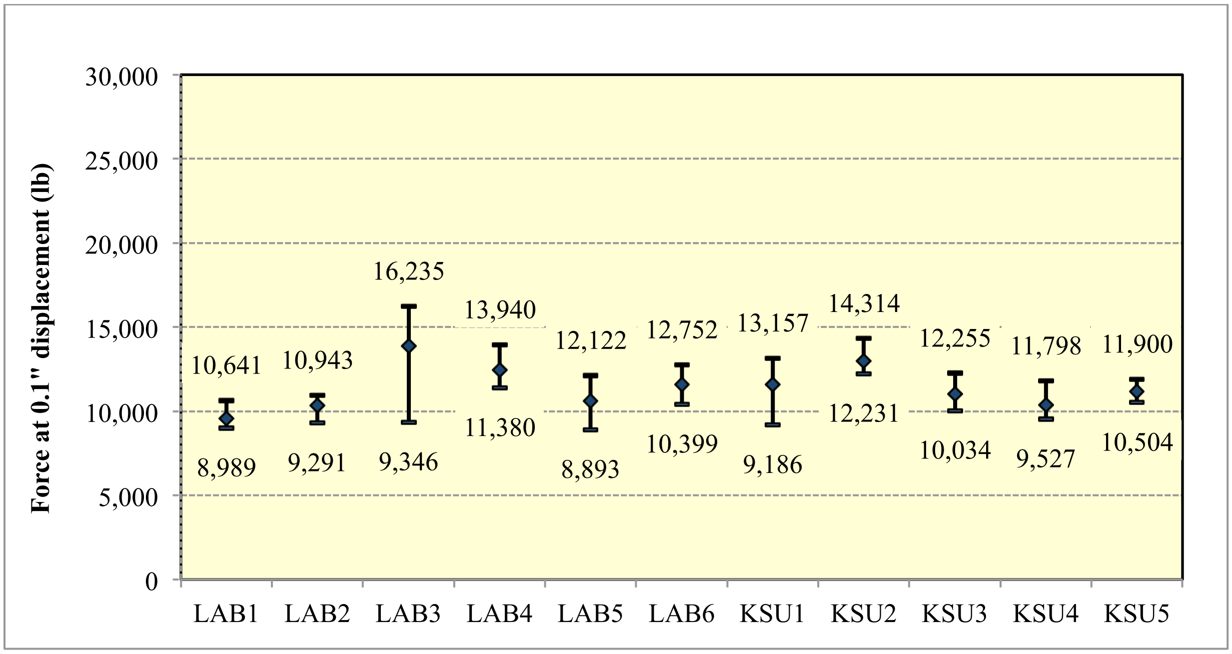

Figure 5 Interlaboratory Study Results, Method B- Strand I

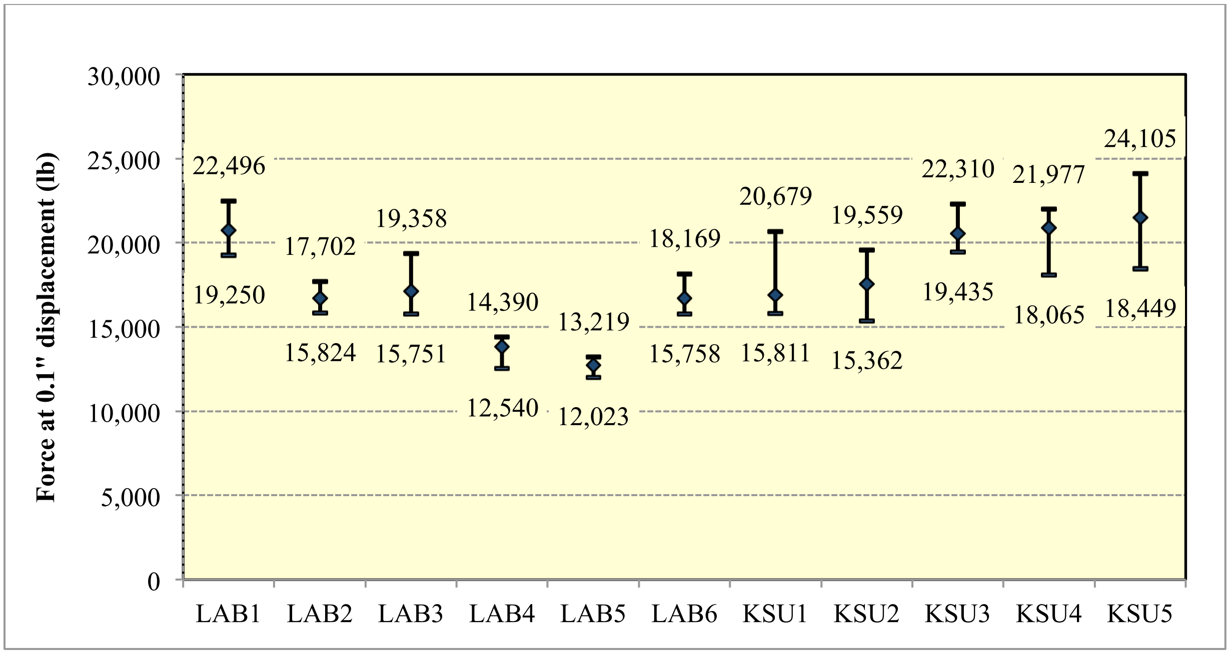

Figure 6 Interlaboratory Study Results, Method A- Strand G

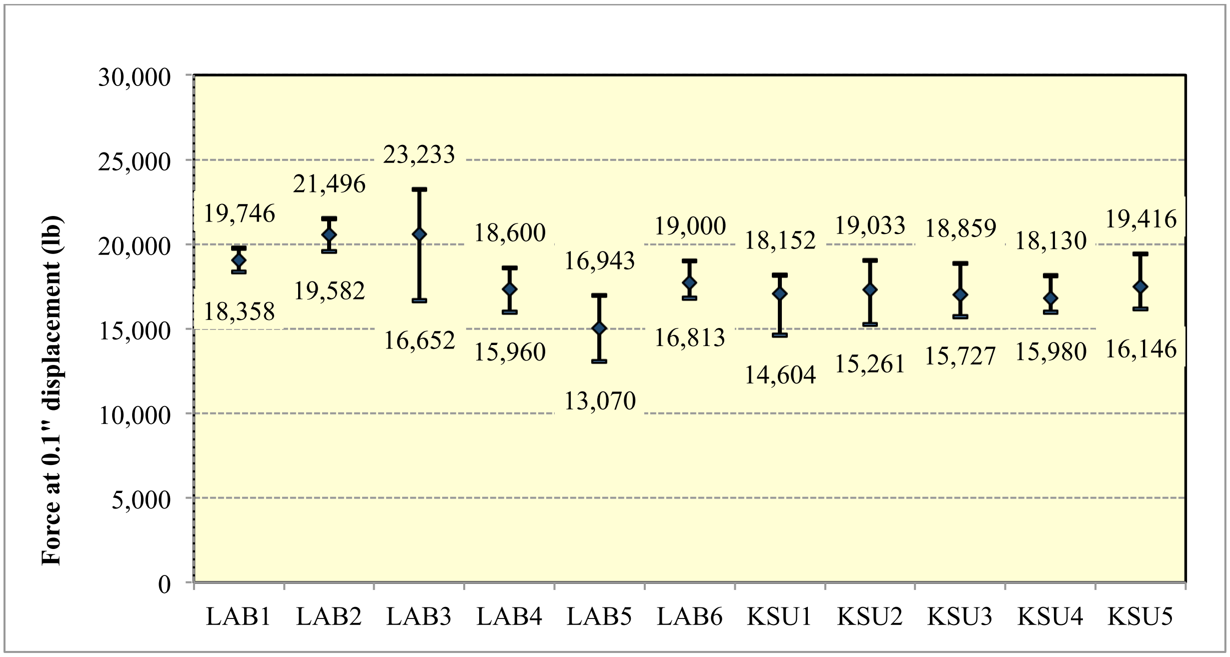

Figure 7 Interlaboratory Study Results, Method B- Strand G

Switching to Method B reduced the variability of the test results within laboratories, as well as total variability when considering the Interlaboratory study as a whole. Average standard deviations and coefficients of variability per strand are shown in Table 8.

Table 8 Average Pullout Test Result, Standard Deviation and Coefficient of Variation for Strands A, G and I, Method A vs Method B

	Strand A Method A	Strand A Method B	Strand G Method A	Strand G Method B	Strand I Method A	Strand I Method B
Average	13500	14300	17700	17800	11600	11400
Standard Deviation	1903	1882	2728	1576	1543	1212
Coefficient of Variation	0.14	0.13	0.15	0.09	0.13	0.11

As observed in Table 8, the average test results for strands G and I when comparing Method A to Method B only vary by 100 lb and 200 lb, respectively. In the case of strand A, the average pullout test result that was obtained when utilizing Method B was 800 lb higher that the average pullout test result obtained by Method A. The standard deviation of the data samples was reduced in every case when Method B results were considered, especially for Strand G, where Method B was able to reduce the variability from a coefficient of variation of 0.145 down to 0.11. This reduction in variability was expected since the ruggedness study results suggested that reducing the mortar mixture flow allowable range would reduce the test variability.

Enforcing a water to cement ratio of 0.45 was also found to reduce the variability when KSU researchers first attempted this method modification, but the outliers obtained during the Interlaboratory study from specific laboratories raise the question of how the duration of sample curing affects specimen performance, while they are at equal compressive strengths. This could be because the mortar cubes were cured at a constant laboratory temperature. The specimens containing strand were stored in moist rooms kept at a constant temperature. Because the specimens have a considerable amount of cement, their heat of hydration can raise the temperature of the specimens significantly, raising the maturity of the samples. This could explain why mixtures with significantly faster or slower reacting cements at the same w/c gave different pullout strengths, even when companion mortar strengths were similar.

CONCLUSIONS AND RECOMMENDATIONS

By using different type III cement sources at the different Interlaboratory study participants laboratories and also within KSU, it was noticed that it was not possible for all cement sources to reach the specified mortar compressive strength of 4500-5000 psi within 22-26 hours from mixing time when using a prescribed water-cement ratio of 0.45. For this reason, the modified ASTM A1081 method proposed imposed no constraints when it came to curing time. This modification to the test method resulted in curing times that varied substantially among laboratories, leading to wariness that differences in mortar maturity at the time of test could cause some strength discrepancies.

The ASTM A1081 test method was found to have a coefficient of variation of 14.5%. Modifications to the test that include using a standard graded sand source at all laboratories, using mortar mixtures of a consistent water-cement ratio (w/c) of 0.45 at all sites, and reducing the allowable mortar mixture flow range reduced the average coefficient of variation to 11%. While it was found that the modifications proposed did reduce the test variability, the use of a standard graded sand source would also raise the cost of performing the test substantially.

Using different cements affected the test results. Further investigation of cement source chemical composition and properties might lead to further recommendations about cement source selection to reduce test variability.

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