EFFECTS OF SETUP AND MATERIAL PARAMETERS ON THE STANDARD TEST FOR STRAND BOND

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ABSTRACT

ASTM recently adopted the Standard Test Method for Evaluating Bond of Seven-Wire Steel Prestressing Strand as ASTM A 1081. The precision and bias statement for this test method has not however been developed. The first step in developing the precision and bias statement is to perform a ruggedness study to determine how the results are affected by allowable variations in methods and materials. A ruggedness study was performed for ASTM A 1081 as the first step in an ongoing interlaboratory study to determent the test method precision and bias. After an initial survey of the pull-out strength of North American Strand in mortar, three strands of differing pull-out strengths were selected for inclusion in the ruggedness study. During this study, the mortar flow, compressive strength at testing, and test loading rate were varied in order to determine their effect on the test results. The results showed that flow was a significant variable in the testing program.

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

INTRODUCTION

ASTM International has recently adopted the "Standard Test Method for Evaluating Bond of Seven-Wire Steel Prestressing Strand", designated as ASTM A1081/A1081M-12 (1). The test method was originally developed by Professor Bruce Russell for the North American Strand Producers (NASP) Association (2). The test aimed to provide a reliable and consistent test procedure to measure the ability of 7-wire prestressing strand to bond to cementitious materials (2). Although the test method has been accepted by ASTM, the precision and bias statement for the test method still needs to be developed. Precision and bias statements are required by ASTM, since they provide confidence regarding the validity of a standard test.

Since the tensile prestressing force applied to pretensioned applications is transferred to structural members principally via the bonding action between the strands and the member material, providing quality bond is a crucial aspect of prestressing. Inadequate bonding performance could lead to longer transfer lengths than expected, unexpected shear cracking, or bond failure causing a structural failure.

The test method was developed in four rounds between the late 1990s and late 2000s at the University of Oklahoma and Oklahoma State University (2, 3, 4, 5). Initially, the Moustafa large block pull-out test, a modified version of ASTM A 981, and the Friction Bond pull-out test were investigated for their ability to quantify the bond of prestressing strand steel to cementitious materials. The Moustafa large block pull-out test was performed for several tests series, including at two separate laboratories, to determine the test repeatability. The modified ASTM A 981 (6) test and the Friction Bond pull-out test were only performed at one laboratory on a single series of testing. The conclusions regarding the Moustafa pull-out test indicated inconsistency between laboratories as well as high variability within test series. The PTI pull-out test and the friction bond pull-out test were found to not reliably quantify the steel bond to cementitious materials (5).

The first round of the NASP testing led to further investigation of the Moustafa and ASTM A 981 pull-out test, as well as development of the NASP pull-out test based on ASTM A 981 modified to use a mortar instead of cement grout (5). The three procedures were examined for their appropriateness for strand bond evaluation and also their reproducibility during the second round of the NASP study (4). It was found that the NASP pull-out test showed lower variability than the Moustafa and PTI pull-out test methods. It was also found that the variability of both the NASP pull-out test and PTI pull-out showed less variability when the pull-out value was measured at 0.1 in. of strand free-end slip instead of at 0.01 in. as specified in ASTM A 981 (4). This conclusion led to the third (3) and fourth rounds of the study (2).

The NASP pull-out test method displayed better repeatability and reproducibility as a pull-out test and better correlation with transfer length measurements than the Moustafa large-block pull-out test and PTI pull-out test. The NASP pull-out test was therefore recommended for adaptation as the standard pull-out testing method for seven-wire prestressing strand (2). The NASP pull-out test was adopted by ASTM International as standard ASTM A 1081 in 2013 (1).

In 2010, a due diligence review of the NASP test method concluded that additional investigation of the NASP test was required prior to the acceptance of the recommended pull-out value acceptance minimum. A round robin study was also suggested in order to determine the reproducibility of the testing method (7).

PCI is currently funding a research project at Kansas State University (KSU) with the aim of establishing the precision and bias statement for ASTM A1081 and developing a rational basis for a minimum acceptance value for strand tested according to ASTM A1081 for use in prestressed concrete applications. The project incorporates a ruggedness study to investigate the effects of the test loading rate, mortar compressive strength, and mortar flow on the standard test, prior to an extensive round robin study which aims to quantify the precision and bias of ASTM A 1081. This paper documents the ruggedness study, which was conducted at KSU in 2012. During the ruggedness study, the three factors that were suspected to have significant effects on the pull-out force values measured by ASTM A1081, were tested as prescribed by ASTM E 1169 (8).

The investigated factors, test loading rate, mortar compressive strength, and mortar flow, were combined in a ruggedness testing matrix in order to quantify the effects of each factor on the test results. An increased loading rate was suspected to result in higher pull-out force values; similarly greater mortar compressive strengths were suspected to increase the pull-out test results, and finally, greater mortar flows were suspected to lower the pull-out test values. The current specification allows the mortar compressive strength to range between 4500 and 5000 psi, and the mortar flow to range between 100 and 125 %. The pull-out test loading rate is currently set at 0.1 in/min, therefore this factor was investigated in order to identify if potentially testing at a 20% faster loading rate will affect the test results, in an attempt to accelerate the process of testing multiple specimens, and ensure meeting the test time window which is set to 22 ± 2 hours from the time the mortar was mixed. A statistical analysis of the pull-out tests performed in this study was conducted to determine the significance of three factors.

MATERIALS

An ASTM C 150 type III cement (9) with the chemical and physical properties shown in Table 1 was used in all of the mortar mixtures made for this study.

Table 1 Type III cement chemical and physical properties

Property	Value
SiO_2 (%)	21.8
Al_2O_3 (%)	4.3
Fe_2O_3 (%)	3.3
CaO (%)	63.3
MgO (%)	1.9
SO_3 (%)	3.3
Na_2O (%)	0.2
K_2O (%)	0.5
Na_2O_{eq} (%)	0.5
Free lime (%)	1.4
Loss on ignition (LOI) (%)	1.6
Insoluble residue (%)	0.4
Blaine Surface Area (m^2/kg)	577
POTENTIAL CALCULATED COMPOUNDS:	
C_3S (%)	49.2
C_2S (%)	25.4
C_3A (%)	5.7
C_4AF (%)	10.2

The sand used for this study was obtained from Dolese Brothers Co, Oklahoma, the same supplier that provided the fine aggregate used for the NASP Round IV Strand Bond Testing study conducted at Oklahoma State University (2). The ASTM C33 concrete sand that was used in this study had an absorption content of 0.26%, specific gravity of 2.59, and fineness modulus of 2.67. The sand was oven dried for 24 hours and then sieved to ensure that there would be no variability in the pull-out test results due to inconsistent aggregate moisture content between the mortar batches. The sand was recombined into a constant gradation according to the sand average gradation in order to reduce variability from differences in sand gradation, according to Table 2.

Table 2 Sand Gradations

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

Eight sets of samples of 0.5-inch diameter, seven-wire, 270 ksi, low relaxation steel strands conforming to ASTM A 416 (10) were tested according to ASTM A 1081. The samples were supplied by six of the major strand manufacturers in North America, and were designated as strands A, B, C, E, F, G, H, and I. All of the strands except strand I were market condition strand. Strand I was a known lower-bonding strand that was supplied by one of the strand producers in order to assist the researchers in identifying a low bond source.

The purpose of the initial strand selection process was to identify one strand source with a pull-out force in each of the following ranges:

a) 10,500-12,500 lb
b) 12,500-15,000 lb
c) 15,000-17,500 lb

Figure 1 shows the average pull-out strengths versus free end displacement for each strand source tested. Figure 2 shows the pull-out strengths at 0.1 in. free end displacement for the six specimens tested and average value for each strand source. Strand A was determined to have an average pull-out force value at 0.1-inch displacement of 14,100 lb during the initial strand selection process, and was therefore chosen as the b) 12,500-15,000 lb range representative strand. Strand I was indeed the only representative of the low pull-out force range a) 10,500-12,500 lb, with an average pull-out force of 10,900 lb during the initial selection process. Strand G had an average pull-out force of 17,800 lb during the initial round of testing, and was chosen as the higher pull-out force value representative for range c) 15,000-17,500 lb. Although strand E had an average pull-out force of 16,700 lb and inside range c, the strand E free-end displacement vs. force curve was not typical, as shown in figure 1.

At least 3000 ft. of strand A, G, and I were obtained from the corresponding strand manufacturers. The longer coils received were retested according to ASTM A 1081 to verify that the strand received was the same as that tested during the selection process. The pull-out test results obtained from testing the coil samples were in agreement with the results obtained by the initial strand selection testing.

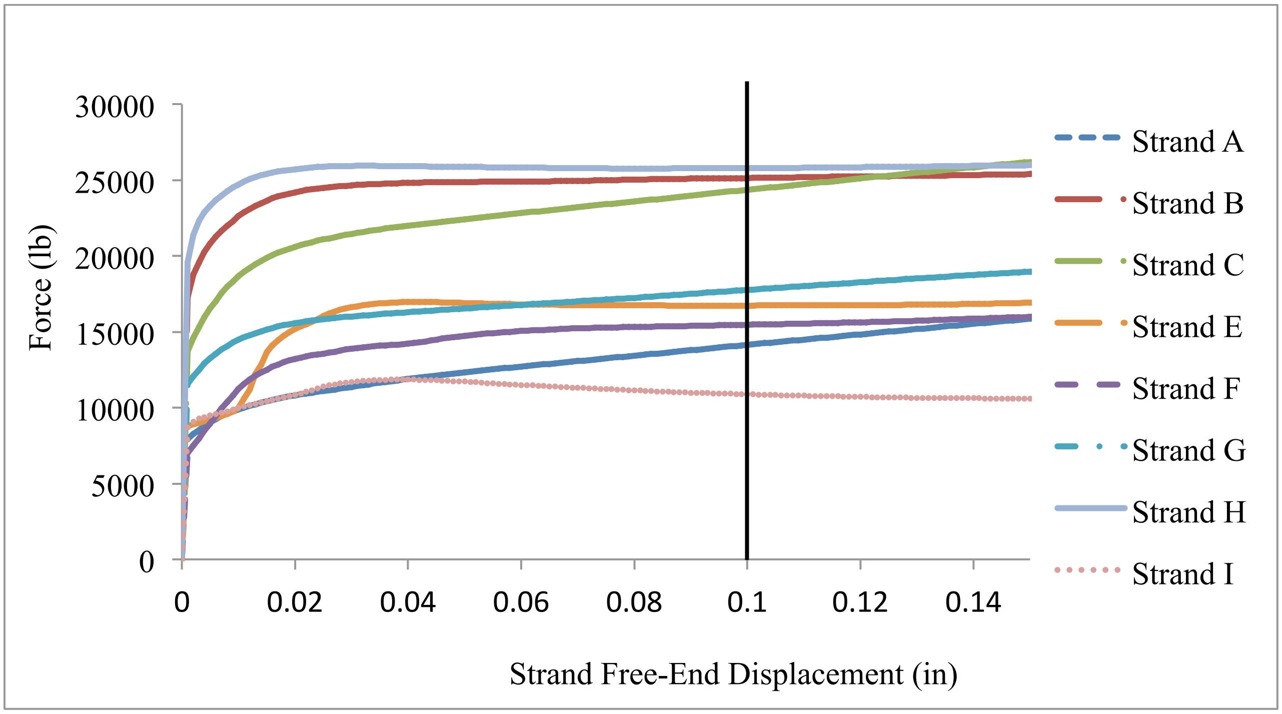

Fig. 1 Average strand force (lb) vs. displacement (in) for each strand supplied

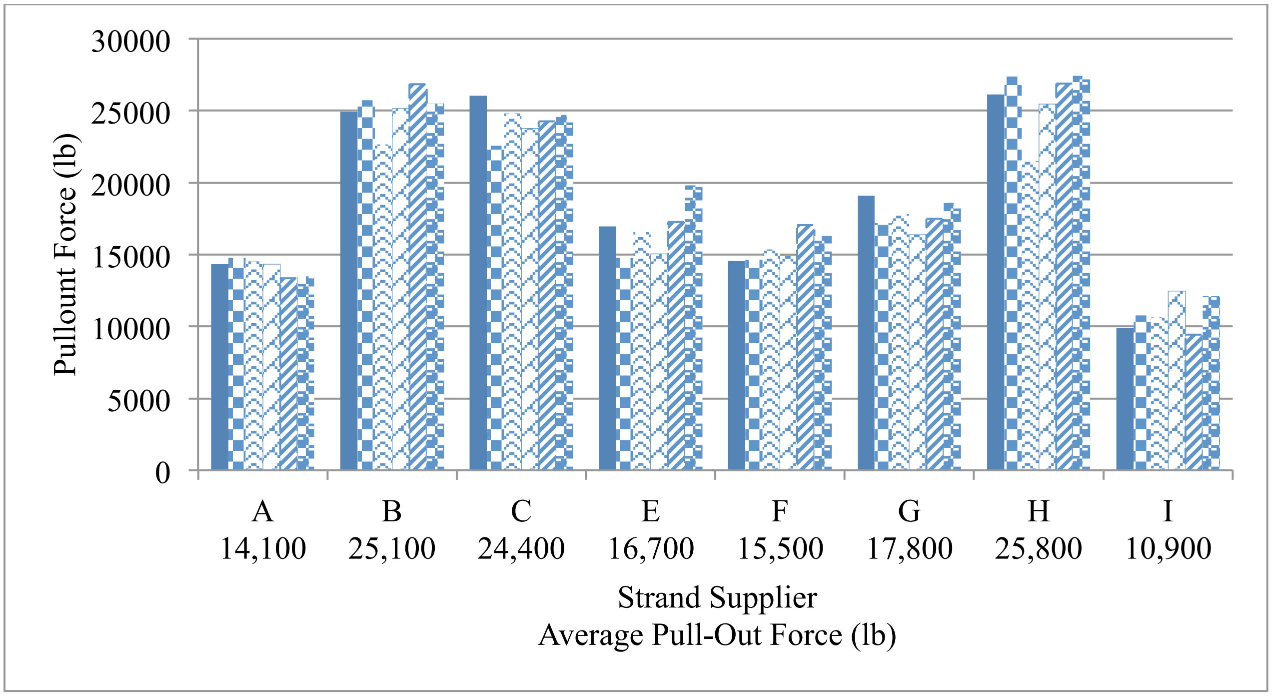

Fig. 2 Pull-out force for six specimens tested per strand source (lb) for each strand source

In order to accommodate the eight combinations of the studied variables, two mortar mixtures were developed for the ruggedness testing matrix, as shown in Table 3. One of the mixtures was developed to have a flow of 100% with the other having a flow of 125%. The water-cement ratio was kept constant at 0.44 for both mixtures but the sand to cement ratio varied. A 2.65 sand to cement ratio was used to target the mortar mixture with a flow of 125%, and a sand to cement ratio of 3.0 was used to target the low mortar mixture with a flow of 100%. The water-cement ratio was 0.44 for all mixtures. The distinction between the two target compressive strengths of 4500 psi and 5000 psi was achieved simply by testing the samples at different times, allowing the mixture develop its targeted compressive strength.

Table 3 Ruggedness Testing Matrix

Test #	Mortar Cube Strength (psi)	Loading Rate (in/min)	Mortar Flow (%)
1	5000	0.12	125
2	5000	0.12	100
3	5000	0.08	125
4	5000	0.08	100
5	4500	0.12	125
6	4500	0.12	100
7	4500	0.08	125
8	4500	0.08	100

METHODOLOGY

Two rounds of testing were performed in June and July 2012 at KSU in Manhattan, KS. The mortar mixtures were mixed in a 12 cubic ft. capacity commercial horizontal shaft hydraulic mortar mixer located in a climate controlled room following ASTM C305 (11). Sample preparation took place before mixing. The 5-inch diameter steel pipes were welded on to 6-inch square plates and sealed before mortar mixing. The specimens were placed on a wooden cart on wheels before mortar placement.

Strand samples were cut to 32 inches. Following the application of 2-inch wide foam bond breaker material where the strand sits on the 6-inch square plate, strand samples were secured in steel cylinders as shown in Figure 3. Painter's tape was used to keep the top surface of the strand clean from any mortar during mortar placement.

Fig. 3 Specimen Setup

After mixing, the mortar flow was immediately measured. The mortar was placed in two approximately equal lifts. An immersion vibrator was used to vibrate the samples after each lift. After vibration, specimens were filled to the top with mortar, finished with trowels, and then wheeled into a 100% humidity room at 73°F for curing. A plastic tarp shielded the top surface of the specimens from any water dripping onto the mortar while curing.

While the specimens were being made, 2-inch mortar cubes were prepared according to ASTM C109 (12). The mortar cubes were covered to protect them from dripping water and cured in the same 100% humidity room as the steel specimens. The mortar compressive strength was tested prior to and immediately after the pull-out testing of the samples.
The 4500 psi and 5000 psi compressive strength targets were achieved by testing at approximately 23 and 28 hours after batch time, respectively. The testing matrix shown in Table 3 was repeated twice. The pull-out tests were performed on a tensile testing frame with a 70,000 lb load capacity. The testing frame which is identified in Figure 4 was fabricated at KSU and uses a thrust bearing to provide torsion-free test conditions, by allowing the specimen to rotate without restrictions.

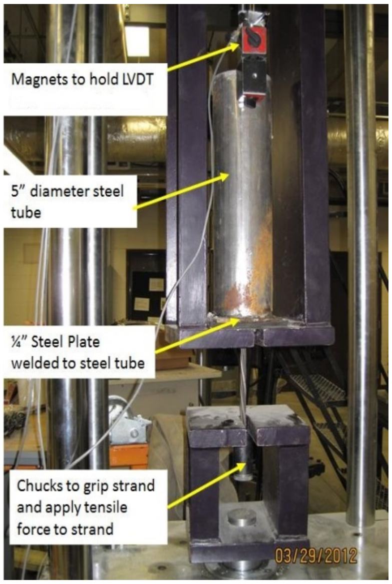

Fig. 4 Tensile Testing Frame

The strand free-end displacement was measured using a linear variable differential transformer (LVDT). The LVDTs were attached to the steel specimens with the use of 2 magnetic bases as shown is Figure 5, allowing for quick setup of the LVDT's tip on the top surface of the center wire of each strand sample.

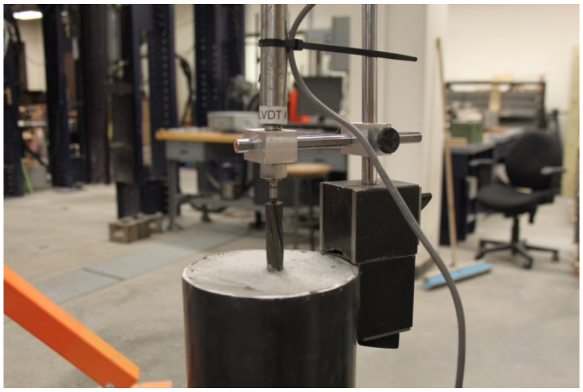

Fig. 5 LVDT setup on specimen

Processing of the test results was executed with the use of spreadsheets, including an analysis of the findings performed as directed by ASTM E1169-07 (8). Additional statistical analysis of the ruggedness study results was completed utilizing the statistical analysis software SAS, in order to confirm the ASTM E1169 results and provide a more accurate representation of the study findings. The results of the study were modeled by three statistical models as part of an analysis of variance (ANOVA).

RESULTS

After the two rounds of testing were completed, the resultant pull-out force average values for each strand supplier were compared in an attempt to identify the effects of each of the three factors on the test results. The testing matrix shown in Table 3 included eight factor combinations tested twice; therefore four groups per factor were comparable in terms of the one factor they had in variance, and since the other two factors were identical for each specific group.

The actual compressive strength values before and after the pull-out tests, along with the actual mortar flow rates obtained for each mixture, and the average pull-out force values are given in Table 4, where the letters A and B designate the first and second rounds of each test respectively.

Table 3 Mortar compressive strengths before and after testing, mortar flow, test loading rate, and average pull-out force values per test

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Test #	Mortar Compressive Strength Before Test (psi)	Mortar Compressive Strength After Test (psi)	Mortar Flow (%)	Test Loading Rate (in/min)	Average Pull-out value (lb) Strand A	Average Pull-out value (lb) Strand G	Average Pull-out value (lb) Strand I
1A	5065	4958	123	0.12	14,194	17,381	12,435
1B	4932	5063	120	0.12	15,410	18,218	12,844
2A	4808	4974	101	0.12	15,065	19,489	12,959
2B	5018	5074	101	0.12	14,763	18,784	13,019
3A	4921	5065	121	0.08	14,577	18,435	10,434
3B	5080	5089	121	0.08	14,489	16,969	11,625
4A	4898	4988	104	0.08	13,931	18,635	11,529
4B	5059	5029	102	0.08	14,336	17,672	12,885
5A	4566	4667	121	0.12	13,952	17,649	10,722
5B	4568	4699	123	0.12	14,312	16,512	12,277
6A	4566	4703	100	0.12	14,313	19,880	12,858
6B	4654	4713	102	0.12	14,783	18,148	11,664
7A	4536	4674	123	0.08	13,657	16,984	11,220
7B	4607	4722	122	0.08	13,336	17,474	11,538
8A	4631	4834	101	0.08	14,737	18,516	12,139
8B	4460	4656	101	0.08	13,875	17,231	12,189

Test groups 1 vs. 5, 2 vs. 6, 3 vs. 7, and 4 vs. 8 were compared to investigate the effect of the compressive strength on the test results, since the mortar flows and test loading rates are consistent per group. As shown in table 5, varying the mortar compressive strength between the two limits set by the standard test specification resulted in a 3.4% difference in the pull-out test values of strand A, a 2.2% difference in the values obtained with strand G, and a 3.0% difference for strand I.

In order to examine the effect of varying the test loading rate, groups 1 vs. 3, 2 vs. 4, 5 vs. 7, and 6 vs. 8 were compared. Each group shares identical compressive strength and mortar flow but different loading rates, with 1, 2, 5, and 6 tested by the higher loading rate of 0.12 in. /min. and 3, 4, 7 and 8 tested at the lower rate of 0.08 in. /min. The results indicate that a variation of the test loading rate by 0.04 lb/in. reflected a difference of 3.4% in the pull-out test results for strand A, 2.8% difference for strand G, and 5.6% difference for strand I.

Test groups 1 vs. 2, 3 vs. 4, 5 vs. 6, and 7 vs. 8 were compared for the purpose of investigating the effect on the pull-out strengths of a mortar mixture flow varying between the two extremes allowed by the standard test specification. The results revealed a 1.6% difference in the test results for strand A, a 5.9% difference for strand G, and a 6.2% difference for strand I. The average difference between the pull-out test results obtained by varying the three factors per strand are summarized in Table 5.

Table 5 Average difference (%) between pull-out test results of test groups per factor investigated

Factor	Strand A	Strand G	Strand I
Compressive Strength	3.4	2.2	3.0
Loading Rate	3.4	2.8	5.6
Mortar Flow	1.6	5.9	6.2

The test method error, calculated after comparing the results from the two rounds of testing, turned out to be 0.7% in the case of strand A, 4.5% for strand G, and 4.2% for strand I. Half-normal plots were created for each of the three strands, following the procedures of ASTM E1169-07. The two-sided tail probabilities (p-values) for each of the factors were calculated for the purpose of developing a half-normal probability plot for each strand. The statistical significance of a factor was evaluated from the p-values, as an effect is considered significant when its p-value is equal to or less than 0.05.

The p-values calculated for the three investigated effects in accordance with ASTM E1169-07 are shown in Table 6 for each of the three strand suppliers. A value below 0.05 probability corresponds to a significant factor in this analysis. None of the factors studied for strand A were found significant according to the ASTM E 1169 analysis. For strands G and I however, the analysis showed that the mortar mixture flow was significant.

Table 6 Two sided tail probability values per effect for each strand supplier by ASTM E1169-07 procedures

Factor	Strand A	Strand G	Strand I
Compressive Strength	0.073	0.263	0.257
Loading Rate	0.070	0.158	0.078
Mortar Flow Rate	0.333	0.013	0.046

Additional statistical analysis using ANOVA models was completed utilizing statistical analysis software. The results were analyzed by three General Linear Models (GLM), with the first one utilizing the mean of the two replicates, and setting the residual sum of squares (residual error) as simply a lack of fit sum of squares (lack of fit), with 4 degrees of freedom.

The second as well as the third GLM utilized all replicate measurements individually instead. GLM#2 modeled the residual error as a combination of lack of fit and pure error having 12 degrees of freedom, and the third model or GLM#3 modeled the residual error as simply pure error with 8 degrees of freedom.

The GLM models yielded a p-value for each case, and these p-values are the indication for the significance of a factor to the test method. If an outputted p-value is equal to or less than 0.05, then we can conclude that the factor is significant, but if the resulting p-value is greater than 0.05, that indicates non-significance of the factor. Since the analysis proved that the error due to lack of fit was present but not significant, it was concluded that GLM#2 represented the data best. The p-values of the three factors by model are shown in Table 7 for the case of strand A.

Table 7 Two sided tail probability values per effect for each ANOVA model used to analyze the data

Strand	Factor	GLM#1	GLM#2	GLM#3
A	Compressive Strength	0.0992	0.0490	0.0575
	Loading Rate	0.0958	0.0463	0.0547
	Mortar Flow Rate	0.3505	0.3008	0.3056
G	Compressive Strength	0.2463	0.3037	0.3528
	Loading Rate	0.1526	0.1879	0.2357
	Mortar Flow Rate	0.0206	0.0123	0.0270
I	Compressive Strength	0.2745	0.2588	0.2831
	Loading Rate	0.1021	0.0711	0.0908
	Mortar Flow Rate	0.0676	0.0379	0.0534

Even though GLM#2 classifies the effects of the compressive strength and the loading rate as significant in the case of strand A, their representative p-values are very close to 0.05, therefore we can say that the effects of the compressive strength and the loading rate were borderline significant to the pull-out test results for strand A. In the case of strand G, all three ANOVA models showed that the only significant effect to the pull-out test values was the variance of the mortar flow. Similarly in the case of strand I, varying the mortar mixture flow proved to be a significant factor for the difference in pull-out test values obtained.

After the analysis of the results from this study, it is recommended that the mortar mixture flow rate requirements of ASTM A 1081 be adjusted to a tighter permissible range in order to improve the repeatability and reproducibility of the test method.

CONCLUSIONS AND RECOMMENDATIONS

A ruggedness study was conducted to investigate the influence of loading rate, mortar compressive strength, and mortar flow rate on the results of ASTM A 1081 "Standard Test Method for Evaluating Bond of Seven-Wire Steel Prestressing Strand". In the ruggedness testing, the loading rate was varied to be 120% and 80% of the specified 0.1 in/minute loading rate. The mortar flow was varied to be at the low and high end of the allowable range of 100% to 125%. The mortar compressive strength was varied to be at the low and high end of the 4500-5000 psi range. Statistical analysis of the results indicated that the mortar mixture flow is a significant factor on the ASTM A 1081 pull-out test results. The current specification allows a range of mortar mixture flows between 100 and 125. It is recommended that the mortar flow allowable range is confined between 105 and 120, in order to reduce the variability of this test method.

Varying the mortar compressive strength between 4500 and 5000 psi was found to not be a significant factor to the test results. The test loading rate was found to be a significant factor in two out of the three strand cases; therefore no modifications can be applied to the specification regarding the loading rate.

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