Interlaboratory study of the standard test method for evaluating bond of seven-wire steel prestressing strand

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- Based on a ruggedness study, a modified method of ASTM A1081 was proposed that changes the mortar flow requirements from 105% to 120%, standardizes the sand source and gradation, fixes the water-cement ratio at 0.45, and eliminates the time window.

- An interlaboratory study was performed using ASTM A1081 and the modified ASTM A1081 method on three different strand sources.

- The ASTM A1081 method and the modified ASTM A1081 method had an average coefficient of variation in the study of 14.5% and 11%, respectively.

Prestressing forces are transferred from the strand to the concrete in pretensioned members by the bond between the concrete and the prestressing strand. A structural engineer will design according to the governing code (for example, the American Concrete Institute's [ACI's] *Building Code Requirements for Structural Concrete [ACI 318-14] and Commentary [ACI 318R-14]*[1] or the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[2]), assuming that the strand is fully anchored at a distance equal to the predicted development length from the beam end, with a reduced steel tensile force and consequent reduced moment capacity in the development-length zone. The reduced prestressing force in the transfer-length zone also reduces aggregate interlock and shear capacity. Reduced shear capacity contribution from the concrete due to reduced prestressing forces resulting from lower levels of strand bond to the concrete can be compensated for by adding stirrups to the member at the end. However, failure can occur when the actual transfer length is longer than the predicted transfer length used in the member design, resulting in a lower shear capacity than the design had predicted.

Prestressing materials of the same type and grade, with the only difference among them being their plant of manufacture, have been found to have significantly variable bonding performance in identical cementitious mixtures.[1–4] There are many prestressing steel properties that can affect the bond between steel and concrete, none of which can conclusively identify strand bond characteristics by visual inspection alone. For example, certain strand surface residue materials can be an important parameter that affects the strand bond to concrete. Lubricants used during the strand drawing process can be partially removed using some washing and heating methods. Any lubricant surface residue remaining after the manufacturing process could change both the chemical adhesion to the cement paste and decrease friction with the concrete after the adhesion breaks and the materials begin to slide past each other.[5–7]

Adhesion is provided by hydration products, such as calcium hydroxide and calcium-silicate-hydrate, that penetrate the porous oxide layer covering the steel surface. Hydration products can react chemically with the steel and grow along the steel surface.[6] Strand geometry is expected to play a role in strand bond to concrete. Once chemical adhesion is broken, resistance to strand slippage is provided by friction. The normal forces and friction forces resisting slippage are dependent on the strand geometry.[6] The speed with which the wires are wound together varies according to the stranding machine and production of each manufacturer, which can affect the mechanical tightness of the strand and assembly of the outer wires to the king wire, potentially affecting the bonding capacity of the strand as a whole.[7–10] Indentations added to the strand are also known to increase bond through mechanical interlock.[11]

Concrete strength and aggregate hardness are known to contribute to bond between steel strand and concrete.[6] High-strength concrete is more resistant to shearing at locations where mechanical interlock prevents strand slippage. High-strength concrete and hard aggregates are better able to resist abrasion wear during strand slippage than normal-strength concrete and soft aggregates.[6]

The beam transfer length and development length of a prestressed concrete beam are two of the primary beam properties affected by strand bond performance. At prestressing plants, end-slip measurements on strand release have traditionally been used to estimate a beam's transfer length. Various untensioned pull-out tests have been proposed as prequalification tests or methods of comparing the relative bond of strands. Attempts have been made over the past couple of decades to develop pull-out tests that could quantify the surface bonding properties of steel strand.

A seven-wire strand bond acceptance test was developed by Saad Moustafa and is, therefore, named the Moustafa large block pull-out test. This untensioned strand pull-out test was performed on 0.5 in. (13 mm) diameter strands embedded in a concrete block to determine if they had enough pull-out capacity to be used as lifting loops. An 18 in. (460 mm) length of the strand specimens was embedded in the hardened concrete and pulled during a process that lasted less than two minutes. The average maximum pull-out force for six specimens was considered a test result.

The ASTM A981[12] test method is performed on a prestressing strand embedded in cement grout in a 5 in. (130 mm) diameter, 18 in. (460 mm) tall steel tube. The strand bond is considered to be the force it takes to pull on one end of the strand and displace the free end of the strand protruding from the steel tube by 0.01 in. (0.25 mm).

The friction bond test is performed by mechanically splicing two bare lengths of strand together and placing the strands in tension until failure of the mechanical splice.

Rose and Russell compared the abilities of these three different tests to predict the bond performance of seven-wire prestressing strand: the Moustafa large block pull-out test, ASTM A981 (the Post-Tensioning Institute [PTI] pull-out test), and the friction bond pull-out test.[13] Results showed that the Moustafa large block pull-out test was consistent in ranking the order of strand bond but was biased by the test location and concrete materials used. The PTI pull-out test method, ASTM A981, was also characterized as reliable in ranking the strands' relative bond performance, but the friction bond test was found to be unable to differentiate the strands' bond performance properly.[1]

A new test method based on the PTI pull-out test was then developed by Russell, who sought to make the test more representative of prestressing strand bond in concrete. The test method has been developed within ASTM as ASTM A1081.[11] Mortar is used in ASTM A1081 instead of cement grout, and the pull-out force is measured when the strand free end slip reaches 0.1 in. (2.5 mm) instead of 0.01 in. (0.25 mm), as in ASTM A981. A previous study of the ASTM A1081 test method by three laboratories using the same 0.5 in. (13 mm) steel strand had a coefficient of variation of 9%; however, a study involving more laboratories was needed to determine the test coefficient of variation for inclusion in the ASTM standard.[7]

To better quantify the test method variability and to develop the test method precision statement, a ruggedness study and an interlaboratory study of the ASTM A1081 test method was conducted using three strands with different bond properties, which were tested at all of the participating laboratories. The average strand pull-out strength for each of the three strands and the test method coefficient of variation determined by the interlaboratory study were compared with the measured transfer length and beam moment capacity of beams made with the same three strands. These results were used to determine minimum acceptance criteria for ASTM A1081 and are reported in a different paper.[14]

Table 1. Testing matrix used in the ruggedness study

Test number	Mortar cube strength, psi	Loading rate, in./min	Mortar flow rate, %
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

Note: 1 in. = 25.4 mm; 1 psi = 6.895 kPa.

Figure 1. ASTM A1081 specimens before mortar placement.

Ruggedness testing

Methodology

A ruggedness study was performed on the ASTM A1081 test method in accordance with ASTM E1169.[15,16] Ruggedness studies are conducted prior to interlaboratory studies to determine potential sources of variability in a test method. Based on the results of the ruggedness study, changes can be suggested to reduce any variability found before the interlaboratory study is conducted. **Table 1** shows high and low variations of the parameters believed to affect ASTM A1081 variability. All of the tests in Table 1 were repeated (two ASTM A1081 tests of six specimens each for each parameter variation) to get an estimate of the test repeatability.

The ASTM A1081 test method was performed by placing 0.5 in. (13 mm) prestressing strand cut to at least 32 in. (810 mm) in length in a 5 in. (130 mm) diameter steel tube that was welded to a ¼ in. (6 mm) thick steel plate with a ⅝ in. (16 mm) hole in the center of the plate. The hole was large enough for the strand to pass through without rubbing. A 2 in. (50 mm) long foam bond breaker was placed around the strand immediately above the steel plate. The strand extended 2 in. above the top of the steel tube and at least 12 in. (300 mm) below the steel plate to allow the strand to be gripped for the pull-out test. The strand above the steel tube was centered using either a metal bracket temporarily attached to the tube or string tied to the strand and attached to the tube.

Figure 1 shows an example of an ASTM A1081 specimen before mortar placement. Mortar was placed in the steel tubes in two layers, with each layer consolidated using an immersion vibrator. After the two layers were vibrated, enough mortar was added to the specimens to completely fill each tube and was struck off level with the top of the tube. The specimens were then moved to cure in a moist room at 73 ± 3°F (23 ± 0.6°C) until companion 2 in. mortar cube specimens made and cured in accordance with ASTM C109[16] reached their desired strength. A plastic tarp was placed over the specimens to shield them from dripping water during curing.

Once the mortar cube samples reached the desired strength, the ASTM A1081 specimens were tested. A linear variable differential transformer (LVDT) was used to measure the strand free-end slip by fixing the LVDT to the steel tube with a magnet and placing the plunger tip on top of the strand center wire (**Fig. 2**). The strand sample wires were gripped using a strand chuck and bearing on a custom torsion-free frame (**Fig. 3**). The tensile frame used had a capacity of 70,000 lb (310 kN). The specimens were loaded at the prescribed frame displacement rate (Table 1) using a closed-loop controller. The pull-out force when the LVDT showed the strand free-end displacement had reached 0.1 in. (2.5 mm) was recorded for each specimen. The pull-out force of six specimens for a given strand and test condition were averaged and considered one test.

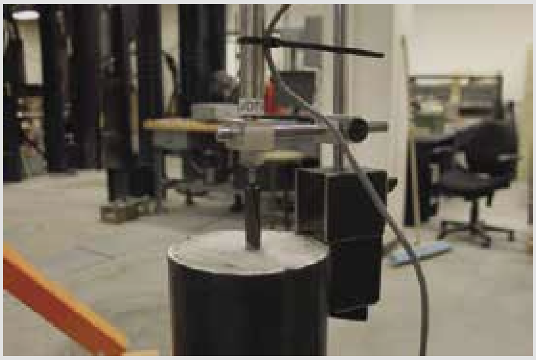

Figure 2. Linear variable differential transducer setup on specimen.

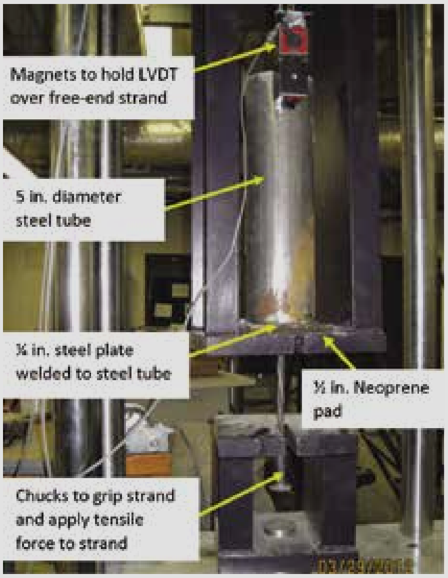

Figure 3. Specimen setup for standard test for strand bond. Note: LVDT = linear variable differential transformer. 1 in. = 25.4 mm.

Materials

Three different ASTM A416[18] seven-wire, 0.5 in. (13 mm) diameter, low-relaxation steel strands were used in this study. The three strands were selected after initially testing eight different strands produced in North America according to ASTM A1081.[15] More than 3000 ft (910 m) of strand was obtained for each of the three strand sources used in the ruggedness and interlaboratory testing.

The same brand and batch of ASTM C150 Type III[19] cement was used to make the mortar for all of the ruggedness tests. An ASTM C33 natural siliceous sand from Guthrie, Okla., was sieved and recombined into a constant gradation (**Table 2**). The fine aggregate had a specific gravity of 2.59 and an absorption capacity of 0.26%. This sand was thus selected because it was from the same source and supplier in Oklahoma that had provided the fine aggregate used in the testing program performed to develop the ASTM A1081 test method.[16] The sand was oven dried before it was used in the testing program to reduce test variability from errors in the aggregate moisture content measurement and consequent corrections.

Table 2. Sand gradations

Sieve	Percentage total	Percentage 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

Two different mortar mixtures were used in the ruggedness testing. The two mortar mixtures were proportioned using a simple mortar mixture procedure developed by the research team to meet both the strength and mortar flow requirements of ASTM A1081.[20,21] This mortar mixture proportioning method determines the water-cement ratio and sand-cement ratio requirements by first testing the mortar cube compressive strength 24 hours after mixing the mortar with two different water-cement ratios but the same sand-cement ratio. A linear interpolation of the mortar compressive strength was used to determine the water-cement ratio that would give 4500 psi (31 MPa) at 24 hours. After the water-cement ratio was selected, the mortar flow was measured in accordance with ASTM C1437[22] on two additional mortar mixtures with the selected water-cement ratio and different sand-cement ratio. A linear interpolation was then used to select the sand-cement ratio that would give the target mortar flow. Both mixtures had a constant water-cement ratio of 0.44, and the pull-out testing time was adjusted in order to measure the ASTM A1081 pull-out strength when the mortar cube strength was between 4500 and 5000 psi (31 and 34 MPa). The first mortar mixture was designed to have a mortar flow of 100% as measured by ASTM C1437. To achieve the 100% flow at a 0.44 water-cement ratio, a sand-cement ratio of 3.0 was used. To achieve the 125% flow required for the second mortar mixture at the same 0.44 water-cement ratio as the first mortar mixture, the sand-cement ratio was adjusted to 2.65.

Ruggedness study results and analysis

Table 3 shows the average mortar compressive strength, mortar flow, loading rate, and average pull-out values for strands tested according to ASTM A1081 with the parameter variations noted. A comparison of the pull-out strength results for mixtures 1 and 5, 2 and 6, 3 and 7, and 4 and 8 (**Table 4**) showed the test result variability caused by a 500 psi (3.45 MPa) difference in mortar compressive strength. A comparison of pull-out strength results for mixtures 1 and 3, 2 and 4, 5 and 7, and 6 and 8 (Table 4) showed the test result variability that a 40% difference in loading rate made. A comparison of the pull-out test results for mixtures 1 and 2, 3 and 4, 5 and 6, and 7 and 8, as shown in Table 4, showed the variability in the test method caused by a 25% difference in mortar flow. Table 4 also shows the test method error calculated by comparing the average of the difference in replicate results for strands A, G, and I.

Half-normal plots were created for strands A, G, and I in accordance with ASTM E1169. Two-sided probabilities (P values) were calculated for each of the ASTM A1081 test parameters studied and each of the three strands used. A two-sided probability was considered statistically significant if it was equal to or less than 0.05. **Table 5** shows the calculated P values for each strand and test parameter.

Table 3. Average mortar compressive strength, loading rate, and average pull-out value for ruggedness tests performed

Test number	Mortar compressive strength before test, psi	Mortar compressive strength after test, psi	Mortar flow, %	Test loading rate, in./min	Average pull-out value for strand A, lb	Average pull-out value for strand G, lb	Average pull-out value for strand I, lb
1A	5070	4960	123	0.12	14,200	17,400	12,400
1B	4930	5060	120	0.12	15,400	18,200	12,800
2A	4810	4970	101	0.12	15,100	19,500	13,000
2B	5020	5070	101	0.12	14,800	18,800	13,000
3A	4920	5070	121	0.08	14,600	18,400	10,400
3B	5080	5090	121	0.08	14,500	17,000	11,600
4A	4900	4990	104	0.08	13,900	18,600	11,500
4B	5060	5030	102	0.08	14,300	17,700	12,900
5A	4570	4670	121	0.12	14,000	17,600	10,700
5B	4570	4700	123	0.12	14,300	16,500	12,300
6A	4570	4700	100	0.12	14,300	19,900	12,900
6B	4650	4710	102	0.12	14,800	18,100	11,700
7A	4540	4670	123	0.08	13,700	17,000	11,200
7B	4610	4720	122	0.08	13,300	17,500	11,500
8A	4630	4830	101	0.08	14,700	18,500	12,100
8B	4460	4660	101	0.08	13,900	17,200	12,200

Note: 1 in. = 25.4 mm; 1 lb = 4.448 N; 1 psi = 6.895 kPa.

The difference in the mortar flow was seen to be significant for two out of the three strand sources tested.

A statistical analysis of the ruggedness study results was performed using a general linear model[15] in which the residual error of the model was compared with the replicate dataset as pure error based on 12 degrees of freedom and a lack of fit. Like the half-normal plot two-sided probabilities, the P values for the general linear model were considered significant if they were less than 0.05. **Table 6** shows the general linear model P values. The variation caused by a change in the mortar flow was shown to be statistically significant for two out of the three strands tested. The loading rate and mortar compressive strength were shown to be significant for strand A using the general linear model. Because the mortar compressive strength and loading rate were shown to be significant for only one strand and one of the analysis methods, the ruggedness test results were not considered to be conclusive. Based on the general linear model analysis and half-normal plots that both showed the mortar flow to be significant for two of the strands tested, it was determined that the reproducibility of the test could potentially be improved by reducing the mortar flow range allowed in ASTM A1081.

Table 4. Percentage difference found in ruggedness study for test parameter variation

Strand	ASTM A1081 test parameter			Test method error, %
	Difference from mortar compressive strength, %	Difference from loading rate, %	Difference from mortar flow, %	
A	3.4	3.4	1.6	0.7
G	2.2	2.8	5.9	4.5
I	3.0	5.6	6.2	4.2

Table 5. Two-sided probability values for each ASTM A1081 test parameter studied

Strand	ASTM A1081 test parameter		
	Mortar compressive strength	Loading rate	Mortar flow
A	0.073	0.070	0.333
G	0.263	0.158	0.013
I	0.257	0.078	0.046

Table 6. Two-sided probability values for general linear model studied

Strand	ASTM A1081 test parameter		
	Mortar compressive strength	Loading rate	Mortar flow
A	0.0490	0.0463	0.3008
G	0.3037	0.1879	0.0123
I	0.2588	0.0711	0.0379

Based on the ruggedness study results, modifications to the ASTM A1081 method were proposed for the inter-laboratory testing. In this paper, the unmodified ASTM A1081 test method will be referred to as method A, and the version of ASTM A1081 modified to account for the results of the ruggedness study will be referred to as method B. A mortar flow range of 105% to 120% was considered to be the smallest practical range that laboratories could be expected to produce and was recommended for method B used in the interlaboratory study. Because the mortar compressive strength and loading rate were only shown to be significant with the general linear model and one strand, no changes for these parameters were made in method B.

In addition, experience showed that achieving a mortar compressive strength between 4500 and 5000 psi (31 and 34 MPa) within the time window specified by ASTM A1081 can be a challenge because of the inherent variability in the ASTM C109 test method. It was thought that reducing the acceptable mortar compressive strength range further would make the test difficult to perform. The time window for performing the pull-out strength was eliminated from method B because time is not a fundamental material property. It was hypothesized that sand gradation, angularity, and hardness could affect the ASTM A1081 results. These sand properties could affect the strength of the mechanical interlock between the sand and the strand. Once the chemical adhesion and mechanical interlock between the mortar and strand are broken, friction is most likely the principal force resisting the pull-out. A harder sand particle could affect the mortar abrasion resistance and, consequently, the pull-out strength. Method B was specified to use the same grade of sand as the ruggedness study to reduce the variability associated with the sand.

Interlaboratory study

Participating laboratories

Nine different laboratories participated in the interlaboratory study. Each of these laboratories was assigned a number designation for reporting results. These laboratories each had the necessary personnel and equipment to conduct the required testing. Prior to performing tests at these laboratories, an instructional training video on the specific details of the test was developed for all of the laboratories to watch and conference calls were initiated with each laboratory to make sure that all of the necessary preparations were made. In addition, a research investigator traveled to each laboratory to observe the testing and to make sure that all of the requirements of ASTM A1081 were met. Because of the prior training provided to each laboratory and the direct observation of the batching and testing protocols, the laboratories conducting the test were all deemed to be qualified.

Materials

Samples of strands A, G, and I were cut and sent to the nine participating laboratories. The same sand used in the ruggedness study was sieved and sent to each laboratory for use in method B. Each laboratory supplied its own ASTM C150 Type III cement for testing according to method A and method B and their own ASTM C33 natural siliceous sand to be used in method A. In addition to the testing performed by the outside laboratories, each strand was tested by the lead laboratory with method A and method B using the sieved graded sand and a different ASTM C150 Type III cement. For method A, each laboratory developed its own mortar mixture that met the requirements of ASTM A1081. All method A mortar mixtures had a mortar flow between 100% and 125% and a strength of 4500 to 5000 psi (31 to 34 kPa) between 22 and 26 hours after mixing. For method B, each laboratory used a water-cement ratio of 0.45 and adjusted the sand-cement ratio to achieve a mortar flow between 105% and 120%. No specified time window was used for method B. **Table 7** shows a comparison of the test requirements for methods A and B.

Results

Two of the external laboratories' mortar mixtures did not meet all of the ASTM A1081 requirements

Table 7. Method A and method B specifications

	Method A	Method B
Time of test, hour	24 ± after mixing	No constraint
Water-cement ratio	No constraint	0.45
Mortar mixture flow, %	100 to 125	105 to 120
Compressive strength at time of test, psi	4500 to 5000	4500 to 5000
Sand source	ASTM C33 sand	Dolese sand, specified gradations
Cement source	ASTM C150 Type III cement	ASTM C150 Type III cement

Note: 1 psi = 6.895 kPa.

Table 8. Interlaboratory study data, method A (ASTM A1081)

Lab	Average mortar compressive strength before test, psi	Average mortar compressive strength after test, psi	Average mortar mixture flow, %	Strand A average pull-out force, lb	Strand G average pull-out force, lb	Strand I average pull-out force, lb
LEAD 1	4550	4700	122.5	12,800	16,900	14,700
LEAD 2	4660	4760	122.4	13,500	17,500	11,400
LEAD 3	4590	4740	118	15,300	20,500	12,000
LEAD 4	4650	4680	124	16,600	20,400	11,700
LEAD 5	4620	4640	122	15,700	21,500	13,400
LAB 1	4630	4790	115	14,200	20,700	10,100
LAB 2	4540	4670	120	10,900	16,700	10,500
LAB 3	4630	4810	117.5	14,600	17,100	12,700
LAB 4	4630	5000	111	11,100	13,800	10,700
LAB 5	4700	4900	120.7	10,700	12,700	9000
LAB 6	4510	4520	123.5	13,200	16,700	11,000

Note: 1 lb = 4.448 N; 1 psi = 6.895 kPa.

(strength, flow, and time) at the time of testing and were excluded from the study, leaving seven laboratories in the study. **Tables 8** (method A) and **9** (method B) list the average mortar compressive strength before and after testing, mortar mixture flow, and pull-out force (average of six specimens) for the three strands tested in the study.

The mortar strength measured by laboratory 6 was significantly lower than the 4500 psi (31 MPa) required for the test. It is believed that this was due to imperfections that existed in the mortar cubes made for the specimens. Pull-out tests for this mixture were begun at the same elapsed curing time at which previous mortar compressive strength tests, performed on the same mixture and

Table 9. Interlaboratory study data, method B (modified ASTM A1081)

Lab	Average mortar compressive strength before test, psi	Average mortar compressive strength after test, psi	Average mortar mixture flow, %	Strand A average pull-out force, lb	Strand G average pull-out force, lb	Strand I average pull-out force, lb
LEAD 1	4530	4490	114.5	14,300	17,100	11,600
LEAD 2	4530	4440	112	14,900	17,300	13,000
LEAD 3	4520	4730	116	13,500	16,800	10,400
LEAD 4	4580	4730	112.7	15,300	17,500	11,200
LEAD 5	4580	4800	116	14,000	17,000	11,000
LAB 1	4650	4710	116	15,300	19,000	9600
LAB 2	4710	4880	113.5	13,400	20,600	10,300
LAB 3	4550	4800	107.5	19,400	20,600	13,900
LAB 4	4480	4820	115	12,700	17,300	12,400
LAB 5	4360	4480	115.3	11,900	15,000	10,600
LAB 6	4010	4120	114.5	13,800	17,700	11,600

Note: 1 lb = 4.448 N; 1 psi = 6.895 kPa.

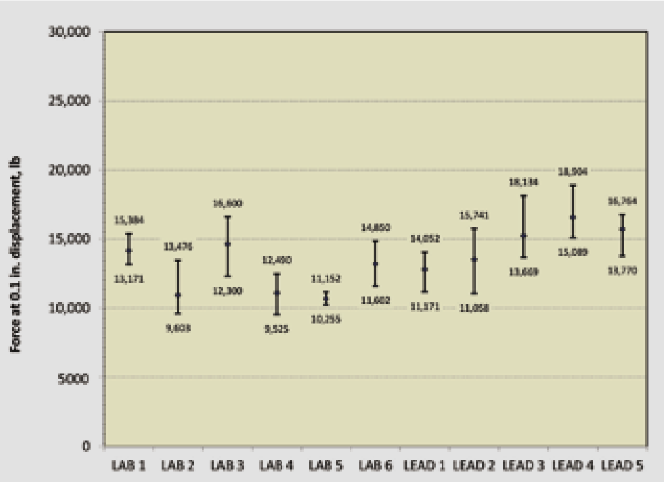

Figure 4. Interlaboratory study results for method A, strand A. Note: 1 in. = 25.4 mm; 1 lb = 4.448 N.

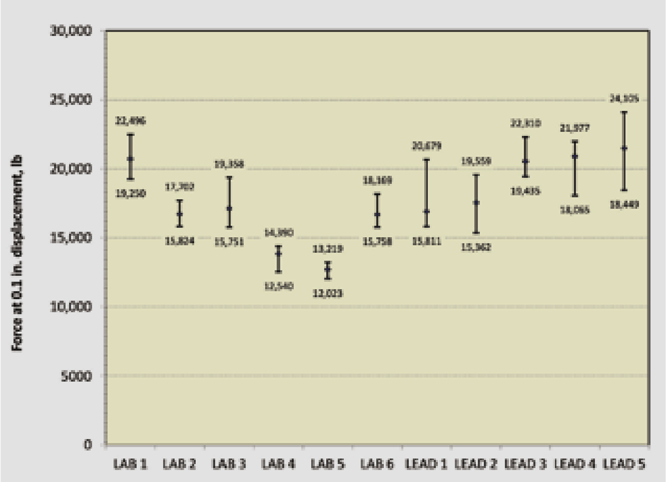

Figure 5. Interlaboratory study results for method A, strand G. Note: 1 in. = 25.4 mm; 1 lb = 4.448 N.

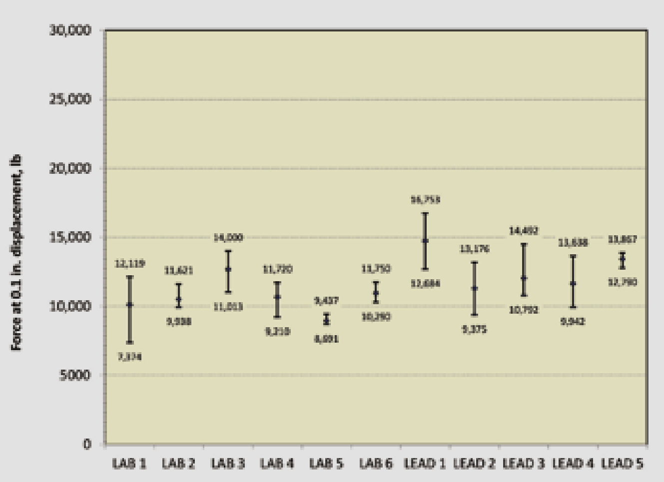

Figure 6. Interlaboratory study results for method A, strand I. Note: 1 in. = 25.4 mm; 1 lb = 4.448 N.

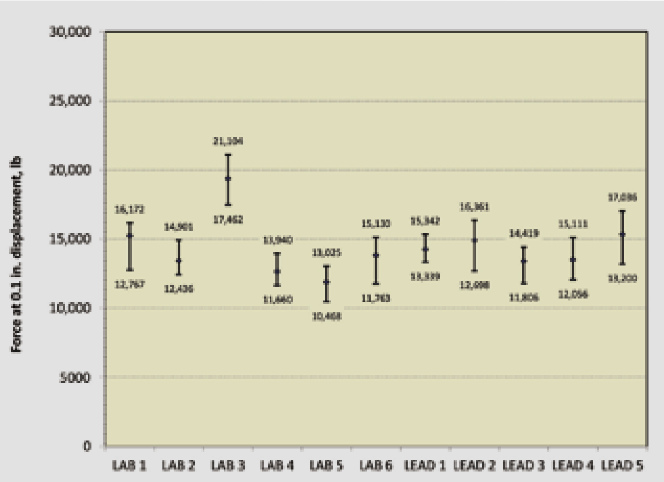

Figure 7. Interlaboratory study results for method B, strand A. Note: 1 in. = 25.4 mm; 1 lb = 4.448 N.

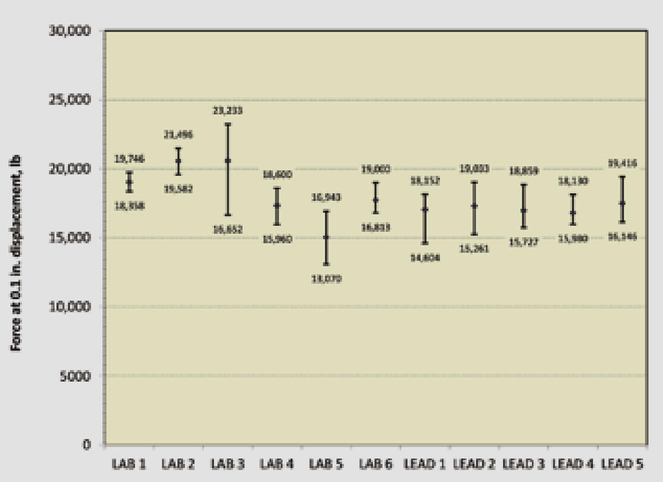

Figure 8. Interlaboratory study results for method B, strand G. Note: 1 in. = 25.4 mm; 1 lb = 4.448 N.

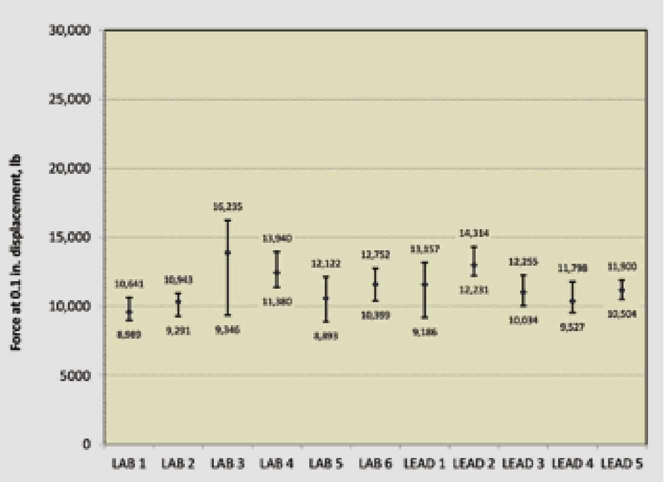

Figure 9. Interlaboratory study results for method B, strand I. Note: 1 in. = 25.4 mm; 1 lb = 4.448 N.

materials, reached the 4500 psi strength. **Figures 4** to **6** show the average of the six specimens tested for the A, G, and I strands, respectively, using method A. Figures 4 to 6 also show the maximum and minimum specimen pull-out strengths measured for each strand tested from each laboratory. **Figures 7** to **9** show the average of the six specimens tested for the A, G, and I strands, respectively, using method B. Figures 7 to 9 also show the maximum and

Table 10. Average pull-out test result, standard deviation, and coefficient of variation for strands A, G, and I for methods A and 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 pull-out force, lb	13,500	14,300	17,700	17,800	11,600	11,400
Standard deviation	1903	1882	2728	1576	1543	1212
Coefficient of variation	0.14	0.13	0.15	0.09	0.13	0.11

Note: 1 lb = 4.448 N.

minimum specimen pull-out strengths measured for each strand tested from each laboratory. These figures illustrate the typical variability of strand bond tests conducted by the participating laboratories.

Table 10 shows the average among participating laboratories with valid test results, standard deviation, and coefficient of variation found for each strand tested using method A and method B. The average values found between method A and method B were similar. The biggest difference noted was the lower coefficient of variation found with method B. The 14.5% coefficient of variation found for method A appears to be high; however, this is similar to other standardized test methods commonly used to test concrete materials. For example, the multilaboratory coefficient of variation for ASTM C1202 is 18%,[24] and the multilaboratory coefficient of variation for ASTM C1260 is 15.2%.[25]

The changes made to ASTM A1081 for method B resulted in a reduced test method variability at individual laboratories and for the interlaboratory study results. The reduction in the test method coefficient of variation for method B was expected based on the ruggedness test results. The test results from laboratory 3 were higher for method B than those measured in the other laboratories. This may be because the mortar compressive strength tests were performed using standard mortar cubes cured according to ASTM C109 with temperatures kept between 69.8 and 77°F (21.0 and 25°C). However, the method B pull-out samples were cured in a moist room. The significant sample size and high cement content in the mortar of the ASTM A1081 samples means that the heat of hydration does not dissipate quickly, leading to a large temperature rise in the specimens, measured to be over 100°F (37.8°C) in many cases. The ASTM A1081 specimens had a higher cementitious material maturity than the small mortar cubes used to measure the compressive strength, which could give the specimens a higher mortar strength than the mortar cubes. This effect would be magnified in mortar mixtures with fast-reacting cements. The mixture used in laboratory 3 gained strength faster than those used in all the other laboratories for method B, probably amplifying this effect.

Future research should investigate the effect of cement type, sand hardness, gradation, and angularity composition and properties on bond. Precast concrete producers should be aware that differences in bond could occur when concrete materials or mixture proportions are changed.

Conclusion

A ruggedness study on ASTM A1081 was conducted according to ASTM E1169 to determine how the measured strand pull-out strength is affected by varying the mortar compressive strength from 4500 to 5000 psi (31 to 34 MPa), the mortar flow from 100% to 125%, and the loading rate from 0.08 to 0.12 in./min (2 to 3 mm/min). A statistical analysis of the ruggedness study results showed that the effects of mortar flow variation were significant within the range specified by ASTM A1081 in strands G and I using both the half-normal plots specified in ASTM E1169 and the analysis of variance method using a general linear model to model the residual error with 12 degrees of freedom used for the pure error and lack of fit.

The same analysis showed that the mortar compressive strength variation within the range specified by ASTM A1081 was not found to be statistically significant for any of the strands tested using the half-normal plot method. The analysis of variance method using a general linear model only found the mortar compressive strength variation within the range specified by ASTM A1081 to be a significant parameter for strand A. The loading rate variation within the range specified by ASTM A1081 was not found to be a statistically significant parameter by either of the statistical methods used. To address the effect that mortar flow could have on the ASTM A1081 test results, changes were proposed to ASTM A1081 to reduce variability. The new modified method, referred to as method B in this study, specified mortar flow requirements of 105% to 120%. In addition, because the water-cement ratio is a material property but time of testing is not, the water-cement ratio for method B was fixed at 0.45 and the time window for testing was eliminated. The sand source and gradation were also standardized for the modified method B to reduce variability from the sand.

The interlaboratory study was performed at qualified laboratories using two test methods on three different strand sources. The first method was according to ASTM A1081 as written (referred to as method A); the second was a modified version of the ASTM A1081 method (referred to as method B). An analysis of the interlaboratory study results showed that the three strands showed an average coefficient of variation of 14.5% for method A and 11% for method B. Although the modifications to the test method for method B reduced the variability, the cost of running method B is considerably higher because of the requirement of using sand from a standard source and with a standard gradation.

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References

1. ACI (American Concrete Institute) Committee 318. 2014. *Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)*. Farmington Hills, MI: ACI.

2. AASHTO (American Association of State Highway and Transportation Officials). 2014. *AASHTO LRFD Bridge Design Specifications*. 7th ed., customary U.S. units. Washington, DC: AASHTO.

3. Russell, B. W., and G. A. Paulsgrove. 1999. *NASP Strand Bond Testing Round I*. Norman, OK: University of Oklahoma.

4. Russell, B. W., and G. A. Paulsgrove. 1999. *NASP Strand Bond Testing Round II*. Norman, OK: University of Oklahoma.

5. Russell, B. W., and G. A. Paulsgrove. 2001. *Final Report—NASP Round III Strand Bond Testing*. Stillwater, OK: Oklahoma State University.

6. Logan, D. R. 1997. “Acceptance Criteria for Bond Quality of Strand for Pretensioned Prestressed Concrete Applications.” *PCI Journal* 42 (2): 52–90.

7. Maehata, T., and H. Ioka. 2006. “Bond Strength of PC Wire in Concrete.” *Wire Journal International* 39 (4): 94–97.

8. Stocker, M. F., and M. S. Sozen. 1970. *Investigation of Prestressed Reinforced Concrete for Highway Bridges, Part V: Bond Characteristics of Prestressing Strand*. Bulletin 503. Urbana, IL: University of Illinois Engineering Experiment Station.

9. Osborn, A. E. N., J. S. Lawler, and J. D. Connolly. 2008. *Acceptance Tests for Surface Characteristics of Steel Strands in Prestressed Concrete.* National Cooperative Highway Research Program report 621. Washington, DC: Transportation Research Board.

10. Gustavson, R. 2004. “Experimental Studies of the Bond Response of Three-Wire Strands and Some Influencing Parameters.” *Materials and Structures* 37 (2): 96–106.

11. Hawkins, N. M., and J. A. Ramirez. 2010. *Due Diligence Review of NASP Strand Bond Test Method*. Chicago, IL: PCI.

12. ASTM Subcommittee A01.05. 2011. *Standard Test Method for Evaluating Bond Strength for 0.600-in. [15.24-mm] Diameter Steel Prestressing Strand, Grade 270 [1860], Uncoated, Used in Prestressed Ground Anchors*. ASTM A981. West Conshohocken, PA: ASTM International.

13. Rose, D., and B. W. Russell. 1997. “Investigation of Standardized Tests to Measure the Bond Performance of Prestressing Strand.” *PCI Journal* 42 (4): 56–80.

14. Riding, Kyle A., Robert J. Peterman, and Thomaida Polydorou. 2016. “Establishment of Minimum Acceptance Criterion for Strand Bond as Measured by ASTM A1081.” *PCI Journal* 61 (3): 86–103.

15. ASTM Subcommittee A01.05. 2012. *Standard Test Method for Evaluating Bond of Seven-Wire Steel Prestressing Strand*. ASTM A1081. West Conshohocken, PA: ASTM International.

16. ASTM Subcommittee E11.20. 2014. *Standard Practice for Conducting Ruggedness Tests*. ASTM E1169. West Conshohocken, PA: ASTM International.

17. ASTM Subcommittee C01.27. 2016. *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)*. ASTM C109. West Conshohocken, PA: ASTM International.

18. ASTM Subcommittee A01.05. 2016. *Standard Specification for Low-Relaxation, Seven-Wire Steel Strand for Prestressed Concrete*. ASTM A416. West Conshohocken, PA: ASTM International.

19. ASTM Subcommittee C01.10. 2016. *Standard Specification for Portland Cement*. ASTM C150. West Conshohocken, PA: ASTM International.

20. Polydorou, T., K. A. Riding, R. J. Peterman, and L. Murray. 2013. "Effects of Setup and Materials Parameters on the Standard Test for Strand Bond." In *The PCI Convention and National Bridge Conference Proceedings, September 21–24, 2013, Grapevine, TX*. Chicago, IL: PCI. CD-ROM.

21. Riding, K. A., R. J. Peterman, T. Polydorou, and G. Ren. 2012. "Simple Mortar Mixture Proportioning Method for Meeting Minimum and Maximum Flow and Strength Requirements." In *The PCI Convention and National Bridge Conference Proceedings, Sept. 29–Oct. 3, 2012, Nashville, TN*. Chicago, IL: PCI. CD-ROM.

22. ASTM Subcommittee C01.22. 2012. *Standard Test Method for Flow of Hydraulic Cement Mortar*. ASTM C1437. West Conshohocken, PA: ASTM International.

23. Polydorou, T., K. A. Riding, and R. J. Peterman. 2014 "Interlaboratory Study for ASTM A1081 Standard Test Method for Evaluating Bond of Seven-Wire Steel Prestressing Strand." In *Proceedings 2014 60th Anniversary Convention and National Bridge Conference, September 6–9, 2014, Washington, D.C.* Chicago, IL: PCI. CD-ROM.

24. ASTM Subcommittee C09.66. 2012. *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*. ASTM C1202. West Conshohocken, PA: ASTM International.

25. ASTM Subcommittee C09.26. 2014. *Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)*. ASTM C1260. West Conshohocken, PA: ASTM International.

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Abstract

As part of a study to determine minimum acceptance criteria for strand bond as measured using ASTM A1081, ruggedness and interlaboratory studies were conducted on ASTM A1081 to determine the test method coefficient of variation. Based on the ruggedness study, a modified method of ASTM A1081 was proposed that changes the mortar flow requirements from 105% to 120%, standardizes the sand source and gradation, fixes the water-cement ratio at 0.45, and eliminates the time window. The interlaboratory study was performed using ASTM A1081 and the modified ASTM A1081 method on three different strand sources. ASTM A1081 had an average coefficient of variation in the interlaboratory study of 14.5% and 11% for the modified method.

Keywords

ASTM A1081, bond, coefficient of variation, strand.

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