STRAND BOND TESTING FOR PRETENSIONED APPLICATIONS: VALIDATION OF THE LBPT METHOD

Nathaniel Sobin, EI, Research Assistant
Dept. of Civil, Environmental, and Architectural Engineering, University of Colorado, Boulder, CO
Micah Hale, PhD, PE, Associate Professor
Dept. of Civil Engineering, University of Arkansas, Fayetteville, AR

ABSTRACT

Strand bond performance for pretensioned, bonded applications was originally measured to ensure that 7-wire strand used in the precast industry was capable of achieving the predicted transfer and development lengths estimated by the corresponding American Concrete Institute (ACI) equations. The bond performance of strands used in research, (an experimental control on strand) has been identified as a secondary need. The Moustafa test method, originally developed to test lifting loop failure, was adapted for the purposes of measuring bond performance and showed strong correlation to transfer and development length in later studies. However, later testing on reproducibility performance between testing sites was found to be less than satisfactory. In response, research was performed in which the Moh's hardness of the coarse aggregate was identified as a key component in sustaining the reproducibility of the test. This change to the Moustafa test method, along with other changes, marked the advent of the Large Block Pullout Test (LBPT). In this study, validation of the LBPT method was performed and the effects of the coarse aggregate hardness (Moh's hardness) were verified to have the effect documented by the previous research efforts. Modifications to the test method are also recommended. Tests performed using the LBPT method also demonstrated effects discordant to previously established strand bond theories.

Keywords: Bond, Large Block Pullout Test

INTRODUCTION

Strand bond and the mechanisms that produce bond have been studied at length since the 1950's. The current motivation for strand bond testing is twofold: to ensure that the estimations for the transfer and development length used by the American Concrete Institute (ACI) are accurate or conservative and to act as a scientific control of the strand in current and future research of pretensioned, bonded concrete applications. The conservativeness of the ACI equations was evaluated several times since its inception with the culmination of these studies occurring in the late 1980's and early 1990's as the original data used to develop the equations was revisited and poor performing marketplace strands were discovered.[1,2] Although the problems documented by this research have faded, a significant quandary still exists within industry regarding how strand producers can ensure that the product they produce is adequate and how consumers (precasters) may be protected from the liability of inadequate strand. Furthermore, a need for measurement of the bond performance of strands used in research, (an experimental control measurement and prequalification of the prestressing strand bond) has been identified as a secondary need.

Strand bond has been studied by several research programs and with varying success. As part of a larger study performed on differing strand bond tests, validation of the Large Block Pullout Test (LBPT) method (a derivative of the Moustafa pull-out test) was performed at the University of Arkansas. Several modifications to the predecessor of this test method have been established, including an additional performance criterion and an additional material requirement for the coarse aggregate used in the concrete mixture. Verification of the performance criteria specified by the new test method on a control strand series with known bond attributes was the key objective. A secondary objective was to verify the previously documented effect of the coarse aggregate on the attainable bond capacity of the strand tested by the LBPT method. Improvements and recommendations to increase both the repeatability and reproducibility of the test method are suggested. Notably, correlation of the test method performance criteria to transfer and development length attainable in structural applications is beyond the scope of this study. This study focuses solely on the repeatability and reproducibility of the test method.

LITERATURE REVIEW

Seminal research in the area of strand bond was performed in 1954.[3] In this research the three key mechanisms of bond were identified as adhesion, mechanical interlocking, and friction. Later research predicated on this study further developed an estimation of bond stress which eventually were accepted as the equations used for estimating transfer and development length.[4] This equation currently appears as equation 12-4 in the ACI 318 code.[5] These equations first appeared in section 2611 of the 1963 ACI-318 Standard Building Code Requirements and Commentary and have received little modification to date.[6] Similarly, the mechanisms of bond have only been slightly modified over time. The term Hoyer effect has become common and is often used in lieu of friction. It is intended to denote both the bond mechanism of friction as well as the physical expansion that takes place due to Poisson's effect following the release of tensioned strands (the initiator of the friction). Later research also suggests that shrinkage and thermal contraction may provide the normal forces required to achieve friction.[7] In regards to untensioned pullout tests such as the LBPT, bond is provided by adhesion (only prior to movement), mechanical interlocking, and friction. The bond provided by adhesion is typically

considered to be negligible leaving the mechanical interlocking and friction forces to solely provide the resistance to pullout. Notably in the LBPT (and other untensioned pullout tests), the Hoyer effect cannot initiate the friction force as the strands are not tensioned and released.
The transfer and development length equations remained in place despite several studies that questioned their ability to conservatively predict development length. A culmination of these studies occurred in the late 1980's and 1990's when a study revisited the data from which the equations were established.[1] This study reanalyzed the original data used to create the transfer length and development length equations and concluded that the equations were unconservative. A later study investigating the development length for epoxy coated strands found uncoated strands that performed well below the development length estimations of the ACI equations.[2] These research findings stemmed many other studies that arrived at a wide variety of conclusions and suggested modifications to the transfer and development length equations.[8,9,10,11] A measure of the attainable bond of the strand (an experimental control similar to the use of concrete strength or slump as a measure of the concrete quality variable) was not reported in these studies.

Research on strand bond experienced resurgence shortly after. Several tests for quantifying bond were developed and comparatively tested to transfer and development length.[12,13,14,15,16] From this testing several test methods emerged. The Moustafa pull-out test (adapted from Saad Moustafa's lifting loop test method) was one of these tests and exhibited a strong correlation to transfer and development length along with a high degree of repeatability.[12] However, subsequent studies on this test method by other researchers found that the reproducibility performance of the test method was unsatisfactory.[14,15] In response, further research by Donald Logan of Stresscon and Robert Peterman of Kansas State University (research results unpublished at this time) was performed and several modifications to the original Moustafa test resulted. These modifications included an additional load performance criterion of 16 kips at "first observed movement" (in addition to the previous 36 kip maximum pullout strength criterion) and an additional material requirement regarding the surface condition of the coarse aggregate used in the concrete mixture. Specifically, the use of a coarse aggregate with a Moh's hardness value of six or greater in the concrete mixture was found to overcome the problems with reproducibility. To explicitly differentiate the test method and its newest modifications from the previous version of the test method it was renamed the Large Block Pullout Test (LBPT).

The need for an accepted strand bond test that provides consistent results is both apparent and overdue. Furthermore, a consensus between strand producers, the precast industry, and academia is vital. A test that is easy to use and replicate could solve the problems previously discussed. The LBPT method shows promise for fulfilling this need for simplicity. Prior to the conduct of the experimental program reported herein, no published research has been performed to validate the claimed effects of the coarse aggregate modifications to this test method through validation to a control strand of known bond characteristics.

EXPERIMENTAL PROGRAM

The objectives of the study were to validate both the performance criteria of the LBPT method on a strand sample with known strand attributes and to document the proclaimed effect of the coarse aggregate in the concrete mixture on the attainable strand bond. The test design and procedure specifications followed the design and procedures outlined in the 1997 paper published in the Precast Concrete Institute (PCI) journal titled "*Acceptance Criteria for Bond Quality of Strand for Pretensioned Prestressed Concrete Applications*" by Donald Logan[12] along with the newly developed additions that denote the LBPT method. The layout and geometry of the concrete block and strand samples are shown in Fig. 1. Modifications to the form design shown included the extension of the longitudinal rebar through the end of the forms so that the form supports the rebar cage and the inclusion of a center rebar cage support consisting of 0.25 inch all-thread (see Fig. 2). Rebar lifting loops were also included in the ends of the block for ease of movement following the test.

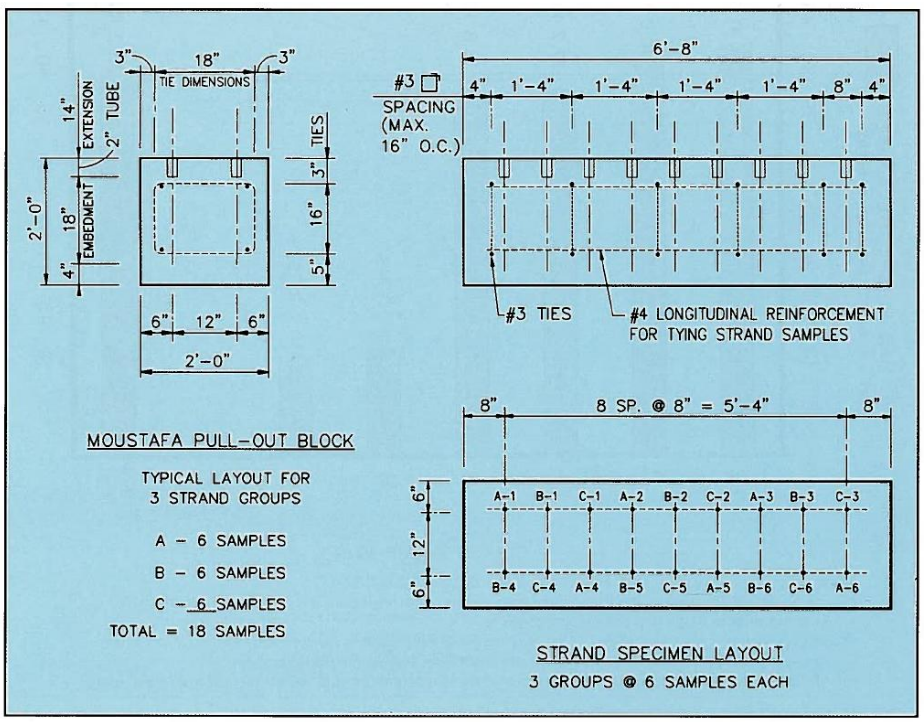

Fig. 1: Test Block and Strand Sample Layout
(Reproduction from PCI Journal v.42, No. 2 p. 88)

Fig. 2: Form and Strand Samples from LBPT at UA

Twelve 0.5 inch diameter, seven-wire strand samples were acquired from three different sources for the tests to be performed (sources named X, Y, and Z for anonymity in this presentation). Thirty six strand samples were tested in total. One strand group with known bond properties served as control while the other two groups were acquired from industry. Strands were tested in the "as received" condition with the exception of the "wipe test" outlined in the 1997 testing procedure. The wipe test showed that all strands tested were free of rust or residue with the exception of group Y. Group Y was found to have a slight "oily" residue. Twelve samples from each of the three strand sources were tested in two large blocks containing 18 strands each. Six samples from each source were tested in a block constructed with a limestone coarse aggregate that did not meet the new material requirement of the LBPT (Moh's hardness of three when the limit is six or greater). Six samples from each of the same sources were tested in a block constructed with a quartz sandstone coarse aggregate that did meet the new material requirement of the LBPT (Moh's hardness of six). Both concrete mixtures approximately followed the suggested mixture of the Moustafa test as outlined in the 1997 test specification. The quantity of sand was altered to account for the change in specific gravity between the two coarse aggregates. Mix quantities are shown in Tables 1 and 2. All concrete mixtures were adjusted for moisture content and well vibrated during concrete placement. Maturity meters were used to adjust the strength of test cylinders to the mass concrete heat effect of the blocks.

Table 1: Quantities for Conforming LBPT Mix (CA with Moh's Hardness of 6)

Constituent	***Quantity (lbs/cy)***
Cement	660
Concrete Sand	1058
Coarse Aggregate (Quartz Sandstone)	1900
Water	292
Mid-Range Water Reducer	33.2 (given in oz/cy)

**All weights given are for constituents at SSD conditions.*

Table 2: Quantities for Non-Conforming LBPT Mix (CA with Moh's Hardness of 3)

Constituent	***Quantity (lbs/cy)***
Cement	660
Concrete Sand	1150
Coarse Aggregate (Limestone)	1900
Water	292
Mid-Range Water Reducer	33.2 (given in oz/cy)

**All weights given are for constituents at SSD conditions.*

The design of the ram and loading yoke used to apply load to the strands followed the original 1997 Moustafa test method specifications and was designed to emulate the prestressing ram used in the original 1997 testing[12] (see Fig. 3). The ram was designed with a sixteen inch stroke and was capable of applying a 20 kip/minute load to the strand specimen. Notably, early iterations of the ram design were unable to apply the 20 kip/minute load rate to the strand only prior to strand slip from the block. The use of a larger hydraulic pump allowed the revised test setup to apply the 20 kip/minute load rate even after strand movement occurred (a mistake often made in the replication of this test method and its predecessor). The sides of the apparatus used to hold the strand chuck were designed to drag against the legs of the ram frame to prevent rotation of the hydraulic during loading, thus again emulating the original test setup. A linear encoder was utilized to accurately measure the movement of the ram (see Fig. 4). A method for more accurately identifying the load at "first movement" is suggested in this study based on the data collected by the linear encoder. Software was utilized to acquire load and ram travel data at a rate of eight data points per second.

Fig. 3: LBPT Test Setup

Fig.4: Linear Encoder

RESULTS AND EXPERIMENTAL ANALYSIS

The LBPT method was successfully performed on thirty-six 0.5 inch diameter 7-wire strand samples in two large blocks. The first block was constructed with a coarse aggregate exhibiting a Moh's hardness of six (conforming to the new LBPT material specification). The second block was constructed with a coarse aggregate exhibiting a Moh's hardness of three (not conforming to the new LBPT material specification). The results for load at first movement and the maximum load achieved are presented in Tables 3-6. Tables 3 and 4 present the pullout load data for the tests conforming to the LBPT material specification (coarse aggregate with a Moh's hardness of six). Tables 5 and 6 present the same data for the tests not conforming to the LBPT material specification (coarse aggregate with a Moh's hardness of three). Tables 3 and 5 present the load at first movement for both blocks and Tables 4 and 6 present the maximum pull-out load for the same.

Table 3: LBPT Results - Moh 6 Coarse Aggregate (LBPT Approved) - Load at First Movement – Graphical Method (kips)

Strand #	***Strand X***	***Strand Y***	***Strand Z***
1	*21.7*	*11.9*	*15.5*
2	*19.4*	*10.9*	*18.7*
3	*19.2*	*11.1*	*15.0*
4	*22.4*	*9.2*	*17.0*
5	*21.6*	*12.3*	*19.6*
6	*20.0*	*11.9*	*21.7*
Average	*20.72*	*11.23*	*17.92*
Std. Dev. (σ)	*1.35*	*1.11*	*2.56*
C.V. (%)	*6.54*	*9.86*	*14.29*
f_{ci} @ Test (psi)	*4850*	*4850*	*4850*
f_c' @ 28 Days (psi)	*8200*	*8200*	*8200*

Table 4: LBPT Results - Moh 6 Coarse Aggregate (LBPT Approved) - Maximum Pull-Out Load (kips)

Strand #	***Strand X***	***Strand Y***	***Strand Z***
1	*42.2*	*32.7*	*38.8*
2	*41.0*	*33.3*	*43.6*
3	*37.4*	*31.2*	*37.8*
4	*38.9*	*35.6*	*40.8*
5	*38.9*	*31.6*	*43.0*
6	*37.5*	*32.3*	*43.1*
Average	*39.32*	*32.78*	*41.18*
Std. Dev. (σ)	*1.92*	*1.57*	*2.45*
C.V. (%)	*4.89*	*4.79*	*5.96*
f_{ci} @ Test (psi)	*4850*	*4850*	*4850*
f_c' @ 28 Days (psi)	*8200*	*8200*	*8200*

Table 5: LBPT Results - Moh 3 Coarse Aggregate (Not LBPT Approved) - Load at First Movement – Graphical Method (kips)

Strand #	***Strand X***	***Strand Y***	***Strand Z***
1	*20.9*	*12.9*	*25.5*
2	*23.0*	*10.8*	*20.3*
3	*25.6*	*9.5*	*23.6*
4	*18.3*	*10.5*	*23.3*
5	*18.6*	*10.5*	*24.1*
6	*22.5*	*9.9*	*17.3*
Average	*21.47*	*10.69*	*22.35*
Std. Dev. ( )	*2.78*	*1.19*	*3.00*
C.V. (%)	*12.93*	*11.17*	*13.45*
f_{ci} ***@ Test (psi)***	*6840*	*6840*	*6840*
f_c' ***@ 28 Days (psi)***	*8010*	*8010*	*8010*

Table 6: LBPT Results - Moh 3 Coarse Aggregate (Not LBPT Approved) - Maximum Pull-Out Load (kips)

Strand #	***Strand X***	***Strand Y***	***Strand Z***
1	*35.4*	*30.6*	*38.8*
2	*40.3*	*30.5*	*38.2*
3	*38.3*	*35.7*	*38.9*
4	*33.7*	*25.8*	*32.3*
5	*35.2*	*27.3*	*32.8*
6	*34.5*	*30.9*	*29.9*
Average	*36.23*	*30.13*	*35.15*
Std. Dev. ( )	*2.53*	*3.43*	*3.95*
C.V. (%)	*6.98*	*11.37*	*11.23*
f_{ci} ***@ Test (psi)***	*6840*	*6840*	*6840*
f_c' ***@ 28 Days (psi)***	*8010*	*8010*	*8010*

The newest performance specification of the LBPT requires a minimum load of 16 kips at first observed movement. Currently the test method suggests that this is to be done visually. This study proposed and evaluated several differing methods for more accurately measuring the load at first movement. The most convenient and accurate means of doing so was a graphical interpretation made possible by the ram travel data collected by the linear encoder. As the strand stretches linearly (without having moved along the embedded length within the block) the slope of the load versus displacement line remains linear. When this relationship becomes non-linear in nature, movement along the embedded length (beyond the stretching of the strand) has occurred, therefore indicating the load at first movement. A straight line was added along the load and ram travel data prior to movement to more clearly determine when movement has occurred. Although still subjective, this method for determining the load at first movement is much less so. Fig. 5 shows this relationship and how first movement may be graphically determined. The data presented in Tables 3 and 5 was determined using this method.

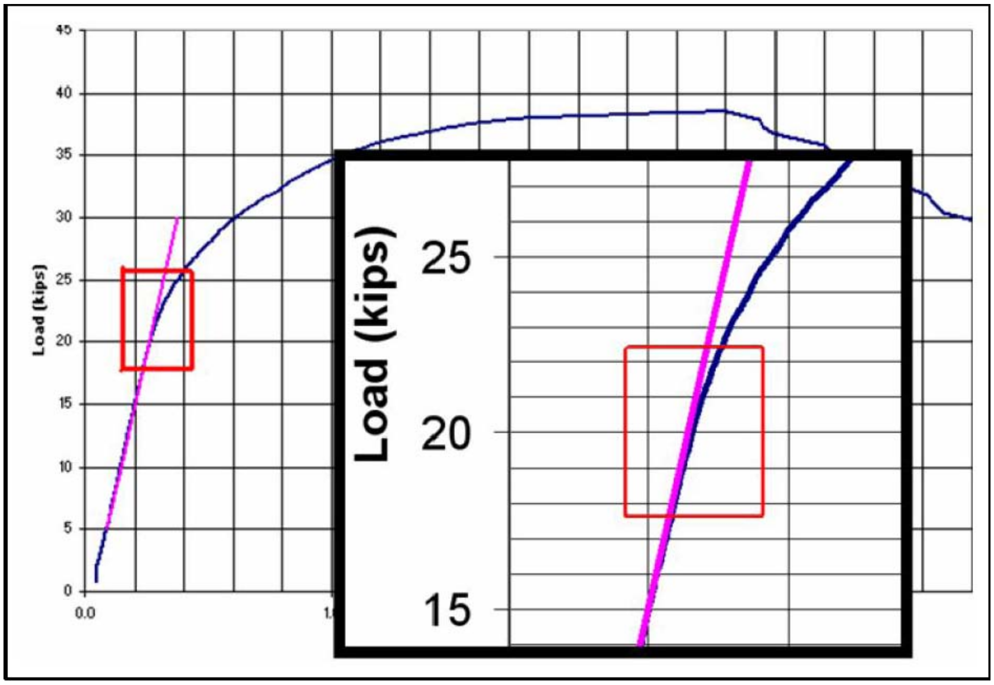

Fig. 5: Graphical Determination of Load at First Movement

DISCUSSION OF RESULTS

One of the study objectives was to validate the reproducibility of the LBPT method between test sites on a strand with known bond attributes. The control of this portion of the study was strand group X as tested in the large block constructed with material properties conforming to the LBPT method (coarse aggregate with a Moh's hardness of six). Strand group X, (provided by Donald Logan of Stresscon Corporation), was known to have a bond capacity exceeding both the 16 kip performance criterion at first movement and the 36 kip performance criterion at maximum pull-out load. As is shown in Tables 3 and 4, strand group X met both of these goals. Furthermore, the mean performance of group X (the control group) at the maximum pull-out load criterion was within one standard deviation of the values acquired at the test site in Colorado on the same strand. However, a statistically significant difference in the means of the load values at first movement did exist. This may be attributed to the differing measurement systems for this performance criterion that were used in the two studies. The variability (repeatability) of the data for strand samples tested in LBPT compliant materials as measured by the standard deviation was quite similar to the data produced from the original 1997 study. With the control established, inferences were able to be drawn on the changes in attainable strand bond with differing coarse aggregates.

The purpose of testing strand samples in two blocks was to identify the effect of the coarse aggregate surface condition (as identified by the Moh's hardness test) on strand bond. Tables 3-6 present the results from this testing. Notably the concrete strengths at testing were significantly different (f_{ci}'). Furthermore, the concrete strength at the time of testing was above the specified limits of the test method for the large block constructed with a non-conforming coarse aggregate (Moh's hardness of three). This result was not anticipated as similar concrete strengths between the blocks would have been ideal for comparative purposes. However, significant findings are still present.

For strand samples tested in the block conforming to the LBPT material standard (Moh's hardness of six), strands from groups X and Z were found to exhibit both high and similar bond performance at both load increments. Moreover, both of these strand groups exceeded the stated performance criteria of the LBPT method at both load increments. Strands from group Y were found to have substandard bond at both of the prescribed performance criteria. This may be explained by the presence of the residue found on the strand sample during the wipe test, but has not been verified. It may also be noted that the group Y strands were obtained from industry, thus indicating that sub-performing strands do exist within the market. However, it must be noted that this statement is reliant on the fact that low performing strands as evaluated by this test method reflect low bond performance in terms of transfer and development length; a conclusion not verified by this study.

The block constructed with a coarse aggregate not in compliance with the LBPT method (Moh's hardness of 3) showed significant deviation from the preceding block in several categories. Notably, the concrete strength at the time of testing (f_{ci}') for this block was significantly higher than the block conforming to the LBPT criteria (6840 psi versus 4850 psi). Past research regarding the effect of concrete strength on strand bond has shown that higher concrete strengths should yield higher levels of attainable bond.[1,9] With this in mind, the measured bond strengths at both increments should have been higher in the second block. The bond strength prior to movement (or at first movement as it is called by this test method) was increased as expected for both of the high performing strands, but not for the low performing strand. A statistical difference in the means was found only for the group Z strands. Notably, the variability of data for all strand groups was increased at this load increment. This could be a function of the higher concrete strength and/or the change in coarse aggregate.

An increase in the data variability was also found in the maximum pull-out load values and with an increased magnitude beyond the induced variability at the first movement load measurement. A significant difference between the means of the high performing strands (strand groups X and Z) was found, but not for the low performing strand group Y. Notably, all maximum pull-out load values consistently decreased when the LBPT was performed with a coarse aggregate exhibiting a Moh's hardness of three (non-conformance with the prescribed LBPT material specification). Moreover, all maximum pull-out load values decreased even when the concrete strength was increased by approximately 40 percent. Given the conclusions of past research it seems highly likely that this is a direct result of the change in coarse aggregate.

The difference in attainable bond between the blocks constructed of differing coarse aggregates may be clarified by revisiting the contributors to bond in different states of bond stress and failure. Previous research delineated two stages of bond failure: a slip at the concrete-strand interface and the destruction of mechanical interlocking forces after slip.[4] It is hypothesized that the bond provided by adhesion, mechanical interlocking, and friction prior to slip is a function of concrete strength while the bond provided by mechanical interlocking and friction after slip is not as influenced by concrete strength. It is also hypothesized that the post-slip bond forces, (the friction and mechanical interlocking bond mechanisms that produce dynamic friction), are primarily a function of the surface condition of the coarse aggregate, similar to the effect of using strands with a weathered surface condition. This appears to be what the Moh's hardness test measures, rather than the actual hardness of the aggregate as the name would imply.

Additionally, most of the high performing strand samples in the LBPT compliant block (coarse aggregate of six) were disfigured and in one case experienced total failure at a relatively normal concrete strength (4850 psi) and with only 18 inches of embedment. It may be noted that the strand failure, occurring prior to bond failure, transpired without the expansive anchoring bond effect realized in tensioned strands (the Hoyer effect). Moreover, this bond contributor was not only missing, but was in reverse since the strands were continuously narrowed as increased load was applied, rather than having ever been in an expanded (anchoring) state. For these reasons, it is also hypothesized that the Hoyer effect may not be as significant a contributor to bond as originally suggested.

CONCLUSIONS/RECOMMENDATIONS

The results of the LBPT method were able to be reproduced on a control strand with known bond characteristics indicating that additional material specifications for this method have improved the reproducibility of this test method. Based on these findings it is suggested by the authors that the LBPT method shows great promise as a beneficial tool for industry and the research community in evaluating and comparing the bond quality of strand for pretensioned concrete applications in both its performance and simplicity. The inclusion of a control stand sample with known bond attributes can allow a comparative evaluation of the bond quality for strand samples from other sources.

The effect of incorporating a coarse aggregate not in conformance with the newest material specification of the LBPT method (as measured by the Moh's hardness test) was verified. The use of a non-conforming coarse aggregate material resulted in decreased bond after initial slip despite a significant increase in concrete strength.

To further enhance the capability of the LBPT as a valuable tool for the industry and for the research community, improvements to the method are suggested that will further increase the repeatability and reproducibility of the test:

- A clearer designation of the load rate (20 kips/minute) after slip should be included in the test specification. Since 0.5 inch strands fail just beyond 40 kips, a single test should take approximately two minutes. Furthermore, a specified variance from the 20 kip/minute load rate should be included in the test specification (i.e. …deviation from the 20 kip/minute load rate shall not exceed a variance beyond 2 kip/minute above or below the specified load rate.)

- The stroke of the load apparatus should be adequate to allow significant strand movement during the test (up to 12 inches or more).

- A statement should be included in the test specification that addresses restraint of strand rotation during loading. Clearly the test setup in the 1997 study (and in this study) shows rotational restraint on the load application apparatus (the ram).

- Given the current range of water reducing products on the market, the water reducer used in the suggested concrete mixture should be either expounded on or eliminated.

- The acquisition of ram travel data should be required in addition to load data so that the determination of first movement can be more easily established. A visual means of determining first movement is too subjective and is not recommended.

- Compensation for the mass concrete heat effect of the block versus the test cylinders used to determine strength of the block should be required in the test specification.

- A suggested level of data granularity and rate of data acquisition should be included in the test specification.

As was previously discussed in the text of this paper, consensus on a standardized strand test is needed by the strand producers, the precast industry, and academia. Although the LBPT method is a simplistic means of testing strand bond, a general improvement to the test method would be to make it more accessible to the strand production industry and academia. Specifically, a reduction in block size would be a welcome change so that smaller concrete batches would be required and the use of testing apparatus more familiar with strand producers and academic institutions could be utilized (i.e. an MTS machine or similar). A final recommendation for this test method, and all other proposed test methods for measuring bond, is to disseminate research findings and the most current test specifications. Furthermore, independent validation of the repeatability and reproducibility of the tests should be both objective and independent. Specifically, a written copy of the test specification should be all that is required to construct and execute the test method with repeatable and reproducible results.

As the bond tests were conducted, several compelling findings emerged regarding the contributors and mechanisms of bond. The concrete strength for the block constructed with a coarse aggregate that did not conform to the material specifications of the LBPT (Moh’s hardness of three) was above its intended strength. Although the concrete strength was approximately 40 percent beyond the comparable test block, the maximum pullout load values for strand samples consistently and significantly decreased for high performing strand samples. Furthermore, the load values prior to slip increased as should be expected. It is proposed that concrete strength may be a strong contributor to strand bond only before slip and not after slip. After slip, it appears that the surface condition of the coarse aggregate may play a major role in the production of the dynamic friction forces that resist pullout (a combination of friction and mechanical interlocking).

The LBPT method is designed to test the bond of untensioned strands. This means that strands tested by this method do not enjoy the additional bond mechanisms of tensioned and consequently released strands (Hoyer effect). In contrast, the anchoring effect of the strands used in this test method is in reverse. As the strands are loaded they experience a narrowing effect instead. Consistent disfigurement and in one case failure of the strand prior to the failure of the bond was observed. These observed occurrences were in relatively normal concrete strength ranges and embedment lengths, indicating that the Hoyer effect may not be as significant a contributor to bond as originally suggested.

REFERENCES

1. Zia, P. and Mostafa, T., "Development Length of Prestressing Strands," PCI Journal, V. 22, No. 5, September-October 1977, pp. 54-65.

2. Cousins, Thomas E., Johnston, David W., and Zia, Paul, "Transfer and Development Length of Epoxy-Coated and Uncoated Prestressing Strand", PCI Journal, V. 35, No. 4, July-August 1990, pp 92-103.

3. Janney, J.R., "Nature of Bond in Pretensioned Prestressed Concrete" Journal of American Concrete Institute, Proceedings Vol. 50, No. 9, May 1954, pp. 717-736.

4. Hanson, N.W. and Kaar, P.H., "Flexural Bond Tests of Pretensioned Prestressed Beams," Journal of the American Concrete Institute, Proceedings Vol. 55, No. 7, January 1959, pp. 783-802.

5. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary (ACI 318R-05)", American Concrete Institute, Farmington Hills, MI, 2002.

6. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-63) and Commentary (ACI 318R-63)", American Concrete Institute, Farmington Hills, MI, 1963.

7. Osborn, A.E. and Lawler, J.S., "Acceptance Tests for Surface Characteristics of Steel Strands in Prestressed Concrete", NCHRP Report 10-62, Transportation Research Board, Washington D.C., 2008.

8. Shahawy, Mohsen A., Issa, Moussa, and Batchelor, Barrington, "Strand Transfer Lengths in Full Scale AASHTO Prestressed Concrete Girders," PCI Journal, V. 37, No. 3, May-June 1992, pp. 84-96.

9. Mitchell, D., Cook, W., Khan, A., Tham, T., "Influence of High Strength Concrete on Transfer and Development Length of Pretensioning Strand," PCI Journal, V. 38, No. 3, May-June 1993, pp. 52-66.

10. Deatherage, H.J., Burdette, E.G., and Chew, C.K., "Development Length and Lateral Spacing Requirements of Prestresssing Strand for Prestressed Concrete Bridge Girders", PCI Journal, V. 39, No. 1, January-February 1994, pp. 70-83.

11. Russell, B. W. and Burns N. H., "Measured Transfer Lengths of 0.5 and 0.6 in. Strands in Pretensioned Concrete", PCI Journal, V. 41, No. 5, September-October 1996, pp. 44-63.

12. Logan, R. D., "Acceptance Criteria for Bond Quality of Strand for Pretensioned Prestressed Concrete Applications", PCI Journal, V. 42, No. 2, March-April 1997, pp. 52-90.

13. Russell, B.W. and Rose, D. R., "Investigation of Standardized Tests to Measure the Bond Performance of Prestressing Strand", PCI Journal, V. 42, No. 4, July-August 1997, pp. 56-80.

14. Russell, B.W. and Paulsgrove, G.A., "NASP Strand Bond Testing Round One: Pull-Out Tests and Friction Bond Tests of Untensioned Strand," Final Report 99-03, Fears Structural Engineering Laboratory, University of Oklahoma, July 1999.

15. Russell, B.W. and Paulsgrove, G.A., "NASP Strand Bond Testing Round Two: Assessing Repeatability and Reproducibility of the Moustafa Test, the PTI Test, and the NASP Bond Test," Final Report 99-04, Fears Structural Engineering Laboratory, University of Oklahoma, July 1999.

16. Brown, M., "Evaluation of Test Methods in Assessing Bond Quality of Prestressing Strand," Graduate Thesis for the University of Oklahoma, 2003.