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The effect of mortar strength on the Standard Test for Strand Bond

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The Effect of Mortar Strength on the Standard Test for Strand Bond

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INTRODUCTION

The Standard Test for Strand Bond (STSB) was developed as a method to quantify the bonding capability of steel prestressing strand. The test is meant to be a uniform, repeatable test to compare and evaluate the different prestressing strands. In addition to the needs of the industry, the design equations used for prestressed concrete rely on the abilities of the strand used. Therefore there is need for a simple, standard test to compare differing strands used in prestressed applications. STSB results rely heavily on the mortar mixture used in the test. This research program analyzed the relationship between mortar compressive strength and STSB pull-out values as well as provided recommendations for testers beginning to develop a mortar mix for use in the test.

LITERATURE REVIEW

The original research in the field of strand bond was performed by Jack R. Janney and published in his paper "Nature of Bond in Pre-Tensioned Prestressed Concrete[1]." Janney identified three factors which contribute to the bond of prestressing strand to concrete; adhesion, mechanical interlocking and friction. Adhesion refers to bonding of the strand to the concrete during concrete hardening. Mechanical interlocking is the force imparted to the concrete by the irregular surface of the strand. Friction is caused by the contact between the hardened concrete and the surface of the steel strand. Friction is often described as the "Hoyer Effect" which refers to the increase in steel area due to Poisson's effect as strands are detensioned [2,3]. Janney's work was built upon in subsequent years and used to develop the original equations to estimate transfer and development length of prestressing strand [2,4].

In the late 1970's and early 1980's, it was found that the transfer length equation was possibly not as conservative as was assumed [2,5]. In 1988 the Federal Highway Administration reacted to these findings by limiting the transfer length equation and banning the use of 0.6 in. diameter, 7-wire prestressing strand. This spurred much research in the area of bond and prestressed concrete. Testing in this period suggested that the ACI equations are not conservative; however no alternatives have been implemented so far [6]. Another outcome of this research was the apparent need for a test to quantify and compare the bonding characteristics of prestressing strand. Three of the tests that have been established to try and meet this need are: The Moustafa pull-out test also known as Large Block Pull-out Test (LBPT), the Peterman beam test, and the Standard Test for Strand Bond (STSB). The Moustafa pull-out test (or LBPT) and STSB are both examples of pull-out tests and the Peterman test is a pass/fail quality assurance test utilizing prestressed beams[7].

PETERMAN BEAM TEST

The Peterman Beam test is a quality assurance test developed by Robert J Peterman in 2009 at Kansas State University to assess strand-bond properties relative to specific concrete mix designs. One of the goals of his research was to develop a simple quality assurance test that precast concrete plants could easily conduct at their facilities. The test involves casting a 6 in. deep by 8 in. wide concrete beam with a single prestressing strand at a depth of 4.5 in.

The test itself involves casting the beam using standard methods for batching, consolidating, curing and detensioning. Then the ends of the strand are ground flush with the beam after curing. The beam is loaded to 85% of its nominal moment capacity at which point end slip and any cracks are observed and documented. This load is sustained for 24 hours after which any signs of distress are noted. Finally the beam is loaded to 100% of its moment capacity for 10 minutes and is considered passing if the beam does not collapse. Peterman offered no specific length for these beams, but a shorter length was desired to ensure smaller loads and a reduced nominal moment capacity since strands would only be partially developed. The loads in this test were intended to be applied by concrete blocks or other heavy dead loads. This decision insured that precasters would always have the necessary materials to perform the test. The ease of performance, ability to test a unique concrete and strand combination and the fact that the test is in some ways analogous to field performance of the strand are the main benefits of the test[7].

MOUSTAFA PULL-OUT TEST

In 1997, Donald Logan of Stresscon Corporation developed a test method based on tests performed by Saad Moustafa. Logan tested strand samples representing a wide range of manufacturers and strand qualities. In his version of the test method 18 strand samples cut to 34 in. in length were inspected visually. These strands were then placed evenly in 80 in. long by 24 in. forms subsequently filled with a concrete mix that achieved 4000 psi at 1 day. After curing overnight, the strands were loaded in tension until they failed in bond, and the corresponding force was recorded. Logan also cast and tested beams to compare the pull-out test results with development lengths for each strand[8]. The test existed in this form until Peterson and Logan revisited it and added two requirements; a Moh's Hardness of 6 or greater for the coarse aggregate used as well as recording load at first slip of the strand. This new version of the test was renamed the Large Block Pullout Test (LBPT) [2]. Some researchers have demonstrated a correlation between values from the Moustafa test and development length[2].

STANDARD TEST FOR STRAND BOND (STSB)

The current incarnation of the STSB began as the Post Tensioning Institute (PTI) Pull-Out Test developed by Dr. A.J. Hyett of Queen's University[2]. The PTI test involved a strand cast in a water-cement grout within a 5 in. diameter by 18 in. cylinder. The strand was allowed to cure for one day, after which it was loaded to 0.1 inch of end slip and this load was recorded[3]. During Round II of research performed by Dr. Russell and Dr. Paulsgrove at the University of Oklahoma for the North American Strand Producers (NASP), the PTI test was modified to create the NASP Pull-Out Test. This new version utilized a mortar which included sand and altered the placement and vibration of the mortar[2, 3]. Round III of NASP testing continued the use of this procedure with no alterations, and other research studies indicated confidence in its reproducibility[2, 3]. Round IV of NASP testing involved trying to refine and tighten the NASP test procedures as well as round robin testing between the University of Arkansas, Oklahoma State University and Purdue University to examine the test's reproducibility between sites and using different strands. This research utilized a standard for the test from 2004 but the results of this research culminated in a 2006 draft of the test procedure which was adopted by the NASP[9].

The current incarnation of the test method is known as the Standard Test for Strand Bond (STSB) and the methods used in this testing program conform to the provisional specifications for this test[10]. In brief the test is performed as follows:

1. A single 0.5 in. or 0.6 in. 7-wire prestressing strand 32 in. in length is placed in a 5 in. diameter 18 in. tall steel cylinder. A sand-cement mortar is cast around the strand in two lifts and is consolidated using a vibrator.
2. In conjunction with the casting of the sample, several sets of mortar cubes are cast. These cubes are cast in accordance with ASTM C 109/C 109M[11]. Additionally, mortar flow is measured as per ASTM C 1437-01[12].
3. All samples are placed in an environmentally controlled room overnight and may be tested if the mortar strengths fall between 4,500 and 5,000 psi at 24± 2 hours[11].
4. Actual testing involves placing the samples in a load frame so the bottom end of the strand is pulled (dead end) and the top end is free (free end). At the free end slip is measured using a linear variable differential transformer (LVDT) and bridge setup.
5. Once 0.1 in. of end slip has been measured, the load is recorded and testing is finished.
6. Mortar cubes are again tested and the average strength before and after must fall between 4,500 and 5,000 psi[11].

The range of acceptable mortar strengths and flow values were established by Russell during round IV testing. The mortar strength range was selected for its reproducibility and because this range was the best at identifying a pull-out value from strands with different bonding characteristics[9]. The flow specification was selected to help ensure consistency between mixes[9].

EXPERIMENTAL PROGRAM

The purpose of this research was to examine the relationship between mortar strength and pull-out force in the Standard Test for Strand Bond (STSB). Strand bond was measured for 0.50 in. and 0.60 in. strands cast in mortar mixtures that possessed compressive strengths that were too low, within specifications, and too high. Two tests were performed for each level of mortar strength.

STSB OVERVIEW

The STSB was developed to quantify the bond of prestressing strands using a standard and repeatable process. The test is performed by casting a 32 in. sample of prestressing strand in mortar inside of a cylindrical steel casing and applying a tensile force to the strand until the free end has slipped 0.1 in. The result is a tensile force corresponding to this amount of movement. This recorded value can then be compared to other STSB results to relate bonding capacity of strands from different sources. The mortar used in the test is limited to a range of average compressive strengths of 4,750 ± 250 psi, but must exceed 4,500 psi before beginning the test. The test must be performed at 24 ± 2 hours with mortar strength tests before and after performance of the STSB. Additionally flow is required to be between 100 and 125%.

MATERIALS

The research program examined the effect of mortar strength on the STSB for 0.5 in. and 0.6 in. prestressing strands. The strands were Gr. 270, low relaxation, seven wire strands. Approximately 1000 ft of both strands was received from the manufacturer and stored indoors until testing. The mortar was composed of Type III cement from a single source and washed river sand also from a single source with a fineness modulus of 2.50. The fine aggregate gradation is shown below in Table 1.

Table 1. Fine Aggregate Sieve Analysis

Sieve	**(% Passing)**
3/8"	100
# 4	98
# 8	92
# 16	80
# 30	58
# 50	18
# 100	2

STSB TESTING EQUIPMENT

An MTS 100 kip load frame and load cell was used in conducting the test. Data acquisition was performed with MTS software. A mild steel frame to hold and test the specimens was constructed in two parts. The top frame held the STSB specimen during testing and the bottom frame provided a resistance surface against the prestressing chuck when tensile load was applied. Both frame sections were constructed of mild steel C-channel sidewalls connected to one inch thick mild plate steel at the top and bottom of the frame. Fig. 1 shows the mild steel frames attached to the MTS load testing apparatus. Milled cold-rolled plate steel was used against the bearing surface of the specimen and the prestressing chuck to help insure that all components of the system were properly aligned and normal to the direction of loading.

Figure 1: STSB Load Frame Apparatus

MORTAR MIXTURES

The mortar mixture proportioning was based on Sobin's earlier research work. Sobin recommended a 1:1.2, fine aggregate to cement ratio at a water to cement ratio 0.44 [2]. After several test batches, the w/c was increased to 0.46 for the mortar mixture that met the compressive strength requirements. The mixture proportions were then adjusted based on the strength requirements. Mortar was mixed in 1 cubic foot batches in wheelbarrows using a hoe. A 1 cubic foot batch produced enough mortar to cast 1 set of 3 STSB specimens and make ample mortar cubes. The mortar was mixed in wheelbarrows because a mortar mixer was not available. Wheelbarrow mixing may have added a measure of variability in the compressive strength results and the flow.

During mixing, the aggregate and cement were dry mixed and water was added incrementally. The mixture was agitated with a hoe until proper consistency and workability was achieved (typically around ten minutes). In some higher strength mortar mixes, a super plasticizer (ADVACast 575) was added to achieve the required flow and improve workability. Batch ratios and mortar strengths arranged from low to within specification to high for 0.6 in. and 0.5 in. strand are contained in Tables 2 and 3 respectively. Note that mortar strengths in tables 2 and 3 represent the averages of three cubes. One batch of mortar was enough to make 3 specimen casings and at least 3 sets of mortar cubes. The STSB specification does not limit the number of mortar cubes that can be made and tested, therefore additional cubes were cast for each batch in order that strength testing could begin 22 hours after casting.

Table 2: Mortar Mix Designs for 0.60 in. Strand Testing

	Mix Design	Cement (parts)	Sand (Fines/Cement)	w/c	HRWR (mL)	f'_c Before Test (psi)	f'_c After Test (psi)	Flow (%)
Low	**1**	1	1.2	0.52	0	3740	3940	130.0
Low	**2**	1	1.2	0.52	0	3880	3680	127.2
In-Spec	**3**	1	1.2	0.46	0	4690	4610	97.8
In-Spec	**4**	1	1.2	0.46	0	4730	4910	80.7
High	**5**	1	1.0	0.42	35	5960	5610	138.9
High	**6**	1	1.0	0.42	50	5720	5380	126.2

Table 3: Mortar Mix Designs for 0.50 in. Strand Testing

	Mix Design	Cement (parts)	Sand (Fines/Cement)	w/c	HRWR (mL)	f'_c Before Test (psi)	f'_c After Test (psi)	Flow (%)
Low	**1**	1	1.2	0.52	0	3860	3780	143.8
Low	**2**	1	1.2	0.52	0	3800	3880	129.5
In-Spec	**3**	1	1.2	0.46	0	4680	4360	100.0
In-Spec	**4**	1	1.2	0.46	0	4830	4500	90.1
High	**5**	1	1.0	0.42	50	5510	5280	132.9
High	**6**	1	1.0	0.42	50	6360	6720	113.9

Once a batch had achieved proper consistency, one researcher would begin making 3 sets of mortar cubes following *ASTM C109 Standard Test Method for Hydraulic Cement Mortars*[11] as referenced in the STSB provisional specifications. While cubes were being cast, a second researcher would perform *ASTM C1437 Standard Test for Flow of Hydraulic Cement Mortar*[12] also specified in the STSB specifications. Typically the second researcher would also begin casting the specimens containing a prestressing strand sample and a 2 in. section of bond breaker. The casings were filled in 3 lifts (the three lifts being 50% of the volume, 40% of the volume, and the final 10% of the volume) and consolidated mechanically using a vibrator. Once all samples and cubes were completed, they were stored together in an environmental chamber at 73^0 F and a relative humidity of 50%. Typically the process of preparing specimens took between 20-30 minutes.

PROCEDURE

After 22 hours passed, 3 mortar cubes would be measured using digital vernier calipers in 6 places to establish an average cross sectional area. The cubes were then broken to determine an average compressive strength (measured in psi). If the samples had reached an acceptable strength, the STSB test could commence. In the case that the cubes had not developed the necessary strength, more cubes could be broken before 26 hours until adequate strength was available. Once the cubes were broken, this data was recorded and three strand samples could be tested.

Strand casings were placed on top of the upper frame of the MTS machine and a 6 in. by 6 in. neoprene pad. The bottom end of prestressing strand was then secured to the lower frame using a prestressing wire chuck. The LVDT and bridge assembly could be placed on top of the strand and finally a load of around 150 lb was applied to seat the chuck. Load was applied by displacing the upper frame at a rate of 0.1 in. per minute. The load when the free end of the strand slipped 0.1 in. was recorded and the load frame would run until the free end was displaced by 0.3 in. After this the load would be removed from the machine and the current sample removed to begin testing a new sample. After all three samples had been tested; three more mortar cubes were broken to establish average mortar strength before and after testing. Typically this procedure would take 30-45 minutes to complete.

RESULTS AND ANALYSIS

As stated in the experimental program, 2 sets of 3 specimens were cast for each mortar strength and strand size. This combination resulted in 36 strand tests which are presented in the data as 12 averages of 3 cylinders. Tables 3 and 4 show the results of compressive strength tests and STSB tests for the 0.60 in. strand samples and 0.50 in. strand samples, respectively.

Table 3: Compressive Strength and Pull-Out Values for 0.60 in. Strand

Sample #	Strand Size	w/c	Batch #	Design Strength	Average Compressive Strength (psi)	Average Pull-Out Strength (lb)
1	0.60	0.52	1	low	**3840**	**13349**
2	0.60	0.52	2b	low	**3780**	**13122**
3	0.60	0.42	1	high	**5780**	**26299**
4	0.60	0.42	2	high	**5550**	**21891**
5	0.60	0.60	1	spec	**4611**	**21070**
6	0.60	0.46	2	spec	**4820**	**23056**

Table 4: Compressive Strength and Pull-Out Value for 0.50 in. Strand

Sample #	Strand Size	w/c	Batch #	Design Strength	Average Compressive Strength (psi)	Average Pull-Out Strength (lb)
7	0.50	0.52	1	low	**3781**	**11712**
8	0.50	0.52	2	low	**3840**	**12857**
9	0.50	0.42	1	high	**5400**	**20254**
10	0.50	0.42	2c	high	**6540**	**21161**
11	0.50	0.46	1	spec	**4520**	**16041**
12	0.50	0.46	2	spec	**4660**	**20126**

Even in the case of low mortar strength samples, the 0.50 in. strands were able to surpass the 10,500 lb. minimum average pull-out force recommended by NCHRP Report 603[13]. The 0.60 in. strand samples also all surpassed the 12,600 lb. minimum threshold.

DISCUSSION OF STSB RESEARCH RESULTS

One objective of this research program was to observe the relationship between mortar strength and the pull-out values collected from the STSB. This trend was observed by Dr. Bruce Russell while he was developing the original NASP test and was one of the reasons for the recommended restriction on the range of acceptable mortar strengths[8]. Fig. 2 presents a graphical representation of the mortar strengths and pull-out values recorded in this research.

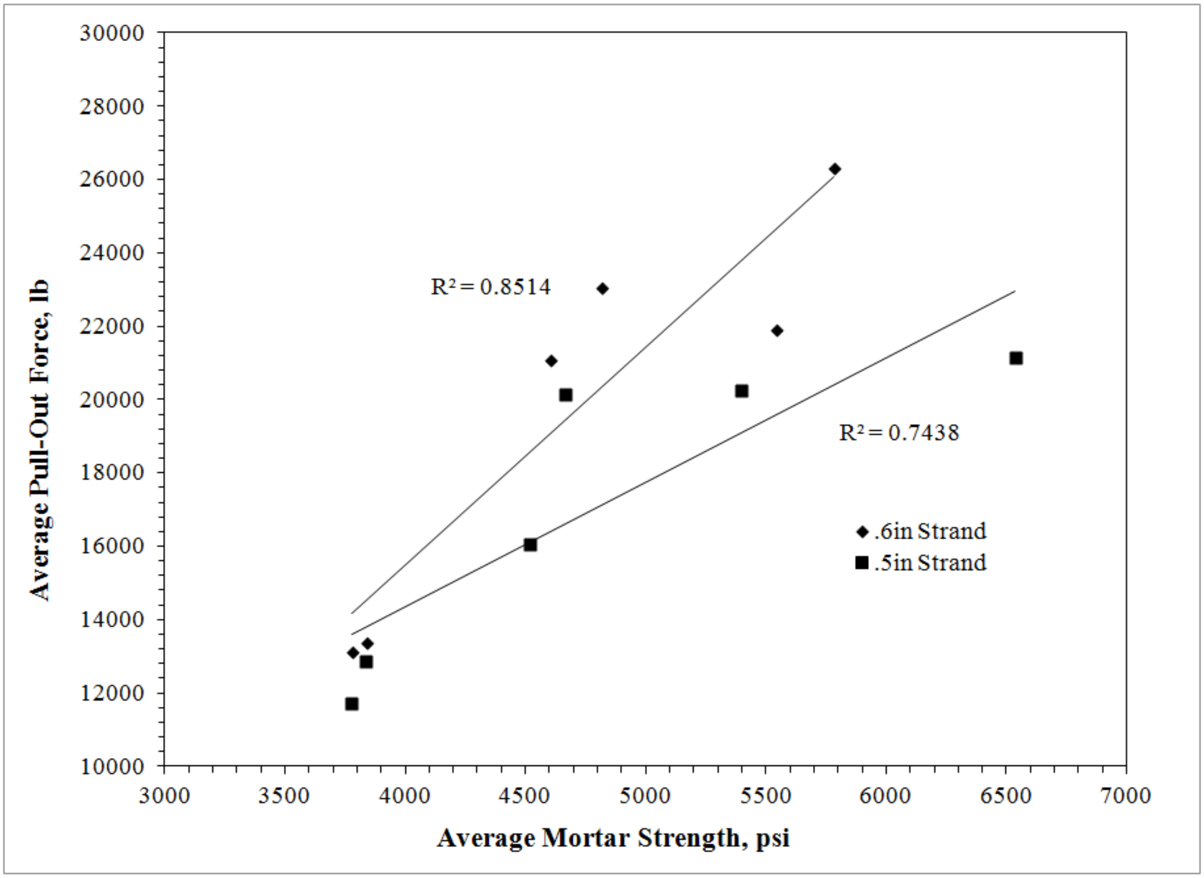

Fig. 2: Mortar Strength vs. Pull-Out Force for 0.50 in. and 0.60 in. Strand Samples

Trend lines are shown on the graph along with R^2 values in order to highlight the clear relationship of pull-out force with increased mortar compressive strength. Although the trend is not ideal, in almost every case, higher mortar strength coincided with a higher STSB pull-out value. As shown in Table 3 and Fig. 2, sample 4 actually had a lower STSB pull-out value than the in-specification test referred to as sample 6. Other than the low results observed in sample 4, the data agrees with the observations of Dr. Russell during his Round IV strand bond testing regarding the relationship between mortar strength and pull-out force.

The relationship between higher mortar strength and higher pull-out force can be attributed to the fundamentals of bond mechanics. Adhesion has little contribution to bond, additionally the friction or "Hoyer Effect" between the strand and the mortar as the strand begins to slip and deform has little effect on pull-out values in this test since the strand deforms and decreases in cross section from the bottom up. Mechanical interlocking is likely the cause of the higher pull-out values. Researchers have shown that as concrete compressive strength increases, transfer and development lengths shorten in prestressed members[15,16,17].

RELATIONSHIP BETWEEN MORTAR STRENGTH AND TEMPERATURE

When developing mortar for use in this test, research performed by Sobin in 2005 was consulted as a starting point. Sobin used a 0.44 w/c ratio, but this value yielded higher mortar strengths than desired and a w/c of 0.46 was eventually settled on for this program. Originally this difference was attributed to the effects of temperature on mortar performance. Because of this, ambient temperature was recorded before every batch in order to establish a relationship between temperature and strength, if one existed. Fig. 3 shows the relationship between ambient temperature and mortar compressive strength.

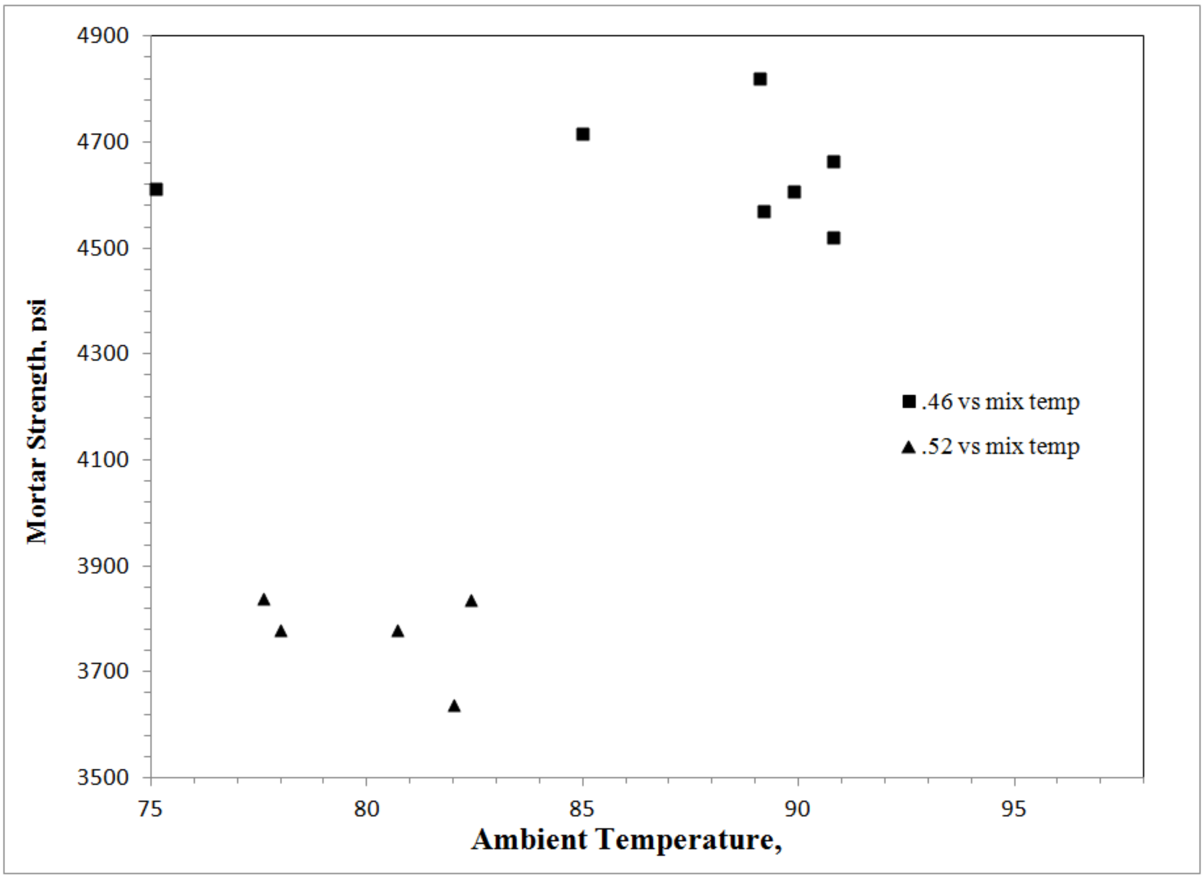

Fig. 3: Ambient Temperature vs. Mortar Strength

Only 0.46 and 0.52 w/c mixes are shown in this figure because the most data were available with these mixes. This figure shows that the relationship between temperature and compressive strength is reasonably negligible at a maximum temperature range of approximately 15°F. The largest range of ambient temperatures occurs for the 0.46 w/c samples, and there appears to be little or no change in mortar strength between the temperature extremes.

CONCLUSIONS/RECOMMENDATIONS

One result of this research program was a deeper understanding of the process of developing a mortar mixture for use in this test. The 500 psi range for compressive strength is quite restrictive for one day mortar strengths using Type III cement. Often, when developing mix designs for this testing regimen, the same mixture could vary substantially from day to day. With experience, these inconsistencies were lessened. Some recommendations for researchers and members of industry beginning to develop a mixture for use in this test include:

- Oven drying fine aggregates for 24 hours and sieving the fine aggregate through a #4 sieve improved the consistency of the aggregate between batches.
- Ultimately the w/c will depend on the material properties of the cement and fine aggregates used, but in this research program, initial trial batches with a w/c of 0.44 to 0.46 produced mortar with a compressive strength near the targeted range.
- For the materials used in this study, a sand to cement ratio of 1.2 appears to be best for use in the STSB. This ratio yielded a workable and repeatable mixture.

The best recommendation for developing mortar for this test is to focus on uniformity. If the same procedure is followed each time by practitioners, the repeatability of the mortar mixtures can be improved. Although mortars used in the beginning of this testing program showed some variance, with experience and practice the consistency of the mixture increased greatly.

Finally, the 4,500 to 5,000 psi range provided in the specifications for the STSB can be difficult to attain. Some observations and recommendations from the pull-out testing performed in this experimental program include:

- It is possible that a quantitative relationship could be established to compare pull-out forces from tests in which the mortar was not within the range of acceptable strengths. It would be necessary to perform tests on a wide range of mortar strengths using the same kind of strand, and perform the program on several strand types and sizes in order to establish a universal relationship.
- Tests in which the mortar strength is below 4,500 psi but the pull-out force exceeds the recommended values from NCHRP 603 could still be considered valid. In this testing program low mortar strength always corresponded to lower pull-out force, so it is unlikely that a test specimen using low strength mortar would yield a higher pull-out force than a test within the acceptable strength range.
- Higher strength mortars could over-represent the bonding abilities of a strand sample. As stated previously, it is possible that a relationship could be established to scale back the pull-out values from these tests.

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