International Journal of Engineering Research and Science & Technology

ISSN 2319-5991 www.ijerst.com
Vol. 4, No. 3, August 2015

Research Paper

SEVEN-WIRE LOW RELAXATION PRESTRESSING TENDON SUBJECTED TO EXTREME TEMPERATURES: RESIDUAL PROPERTIES

John J Myers[1]* and Wendy L Bailey[2]

*Corresponding Author: John J Myers ✉ jmyers@mst.edu

The use of cold-drawn prestressing steel as reinforcement in concrete is common among bridge design throughout the world. This composite material is particularly useful for designs consisting of large spans where the dead load will cause significant cracking and deflection. Unlike mild steel reinforcement, prestressing steel is stressed and cause a compression force within the concrete. This prevents cracking and increases the structure's capacity. A prestressed concrete member will also have a longer life expectancy due to the prevention of cracks. Without cracks the steel will not be exposed to the environment and therefore will be at a reduced risk of corrosion. The increased capacity, ability to sustain longer spans, and durability make this type of material an advantageous choice of construction. This paper investigates the residual properties of seven wire, uncoated, 0.5 in. (12.7 mm) and 0.375 in. (9.5 mm) diameter low relaxation grade 270 ksi (1862 MPa) prestressing tendon subjected to extreme temperature. The temperatures selected for the study were 500°F (260 °C), 800°F (427 °C), 1000°F (538 °C), 1200°F (649 °C), and 1300°F (704 °C). The upper limit was defined by the furnace's capability at Missouri S&T. In addition, control specimens were tested for each strand size. A control was defined as exposure to approximately 68°F (20 °C). Two cooling methods were also investigated, namely inside the furnace and outside the furnace. Test results presented include visual observations, yield stress, ultimate load, and elastic modulus.

Keywords: Low-relaxation seven-wire tendon, Elastic modulus, Extreme temperature property effects, Tensile strength, Ultimate load, Yield stress

INTRODUCTION

It may be argued that bridges are the most effective way to move commerce across bodies of water or low-lying elevations. They provide means for trade and communication to travel across land quickly and efficiently. However, as with any structure there lies the risk of damage or destruction, which can be attributed to a

[1] Ph.D., PE, Missouri University of Science and Technology, Rolla, MO.
[2] Burns & McDonnell, Kansas City, MO.

number of sources. Natural disasters, such as a hurricane or tornado, accidents, such as spilled gasoline tankers, or terrorism are all possible and common causes for damage to a bridge's structural integrity. Often the damage due to extreme events to the bridge is quite severe keeping the bridge out of commission for a large extent of time.

In particular, fire damage is a common and severe cause of destruction caused by many different disasters. It is difficult to recover quickly from these incidents because very little is known regarding the extent of damage caused by a fire to a bridge. Accidents such as the Bill Williams River Bridge in Arizona as well as a number of exploding tankers in Iraq have brought to light the frequency of fire on bridges and the crippling results the damage has on society afterwards. The result is often a complete repair of the bridge which proves to be costly and creates problems with traffic flow. In some cases a trade route is completely closed requiring travelers to travel 100 miles (161 km) or more out of their way to reach their destination.

There are a number of studies which have been performed on Prestressed Concrete (PC) bridges following fire damage. However, this research is either limited to the exterior of the bridge or is performed by decomissioning the bridge and testing components of it in the lab.

Internal observations and flexural strength testing cannot be performed on existing bridges. However, with an increase in the understanding of how fire and extreme temperature affect the bridge an educated decision on the structural integrity of the bridge will be able to be made without laboratory testing. This will result in fewer repairs and minimize the economic and commercial implications typically caused by fire damage.

RESEARCH PROGRAM OBJECTIVES

The objectives of this overall research program were undertaken in three primary phases. Phase I was undertaken to determine properties for grade 270 low relaxation seven-wire prestressing strands before and after exposure to elevated temperatures. This task was undertaken to assemble and add to the present data base to help understand the extent of damage when seven-wire prestressing strands are exposed to high temperatures. Phase II studied the bond stress between High-Strength Concrete (HSC) and grade 270 low relaxation seven-wire prestressing strands after exposure to elevated temperatures. HSC was selected since minimal data existed regarding bond stress of HSC exposed to elevated temperatures. Phase III implemented the results from the first two phases to develop an improved understanding of Prestressed Concrete (PC) bridge behavior after exposure to fire including thermal heat transfer using Finite Element Modeling (FEM). Fire damage to PC bridges is an occasional occurrence, yet investigation of the fire is still very difficult and time consuming. This paper details the results of Phase I. Future publications will disseminate Phase II and III results and findings.

SCOPE

Laboratory testing included two types of prestressing strand testing, tension (Phase I) and pullout (Phase II). Tension results are presented herein. Tests were performed on strands which had been exposed to elevated temperatures and allowed to cool. The data obtained from the tension testing gave an understanding of the tensile strength and stiffness properties of the prestressing strands subjected to elevated temperatures used in subsequent phases of study.

TENSION TESTING

General

Tension tests for steel are all governed by ASTM E8-04 "Standard Test Methods for Tension Testing of Metallic Materials." This document provides specific detail as to how the test shall be performed and the results analyzed. ASTM A370-07a also provides information for all types of steel testing (tension, bend, hardness and impact) and gives specific guidelines based on different types of bar products (fasteners, round wire, multi-wire, etc.).

Prestressing Strands

In addition to the general specifications for tension testing of steel, ASTM A 416/A 416M-06 and ASTM A370-07a Annex A7 have also been published as governing standards for the tension testing of seven-wire prestressing strands. Within ASTM A370-07a Annex A7 a recommended procedure and apparatus are given. Due to the geometry of the strand, a specific method is not required and it is acceptable to employ a method of choice as long as the strand meets the minimum breaking strength given by ASTM A 416/A 416M-06. Guidelines for determining the yield strength and elongation are also given by both specifications.

LITERATURE REVIEW

Fire Damaged Materials Found in Bridges

Materials which are commonly affected by bridge fires include the concrete, prestressing strands and mild steel reinforcement. The amount of information regarding the fire damage properties varies by material. Within this research residual properties of any material are defined as the property of the material after it has been heated and then cooled back to room temperature.

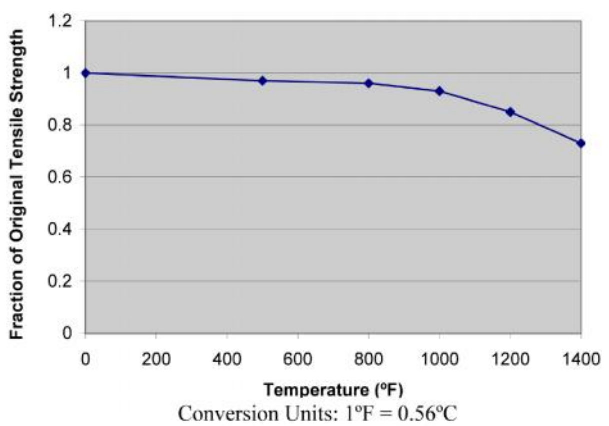
Concrete

Concrete damage caused by fire has been widely researched. A significant amount of data has been published which allows engineers to understand the compressive strength properties of concrete during and after fire exposure. Since the focus of this paper deals with tendon characteristics, further discussion is not presented. However, Moore and Myers[8] provide a detailed literature review on normal strength and high strength concrete as it relates to fire damage that may be referenced for further detail.

Mild Steel

Similar to concrete, damage caused by fire to mild reinforcing steel has been widely researched. The reported properties[3] for grade 60 mild reinforcing steel are illustrated in Figure 1. The modulus of elasticity was found to remain the same for elevated temperatures despite the decrease in tensile strength[4].

Figure 1: Residual Strength vs. Temperature for Mild Reinforcing Steel (adapted from Dias, 1992)



PRESTRESSING STRANDS

In contrast to concrete, much less research has been performed to understand how elevated temperatures physically affect the properties of prestressing strands.

Tensile Strength of Prestressing Strands

Guyon[4] reported the earliest known data regarding the tensile strength of prestressing strands (unreported strand type) exposed to elevated temperatures. The research consisted of hotstressed, hot-unstressed, cold-stressed and cold-unstressed tests. Temperatures varied by test scenario, but no more than four temperatures were chosen per scenario. The type of strand also varied, 0.2 in. (5.08 mm) cold drawn, 0.2 in. (5.08 mm) rolled, and 0.1 in. (2.54 mm) cold drawn. From the testing performed it was found that for stressed specimens tested while heated there is an initial increase in tensile strength up to 302°F-482°F (150 °C-250 °C). Thereafter a significant loss of tensile strength occurs. For unstressed specimens tested after cooling, a constant loss in tensile strength occurs as temperature increases. However, the loss in tensile strength is smaller than that of the stressed specimens for temperatures of 572°F (300 °C) and greater. For this test program the heat soak time was also varied. In these cases a greater loss of tensile strength was seen for specimens heated longer.

Abrams and Cruz[1] performed an in-depth investigation of the behavior of seven-wire, stressrelieved prestressing strands and temperature. The test program consisted of three sevenwire strand sizes 0.25 in. (6.35 mm), 0.375 in. (22.23 mm), and 0.438 in (11.11 mm). During testing, failure modes were witnessed to be either a few wires breaking, followed by the remainder of the wires breaking singly or all the wires breaking at the same time. Abrams and Cruz[1] noted that although the failure mode varied the data did not differ significantly; therefore the failure modes were acceptable.

Also addressed by the researchers was the rate of heating and cooling. By heating several strands up at various rates and then testing, it was determined that the failure was independent of the heating rate. For the cooling analysis several strands were also heated up and then allowed some to cool “fast” and “slow”. Fast cooling was defined as removing the specimens and placing them under a stream of cold water for 10-20 seconds until they returned to normal temperature. Slow cooling was where the specimen was left in the furnace several hours until it reached normal temperature. Based on tension testing following cooling, it was found that the failure was also independent of the method of which it was cooled. Abrams and Cruz also performed tension tests on specimens at elevated temperatures. It was found that the tensile strength sharply decreases at 200°F (93 °C) and continues until reaching 5% residual tensile strength at 1400°F (1860 °C).

In 1967 Abrams and Erlin[2] performed a follow-up to the previous research where the effects due to exposure time were examined and hot and cold tensile strengths were compared. For this research 7-wire, stress-relieved prestressing strands were also tested. Exposure times tested were 1 hour, 4 hours and 8 hours. For these exposure times, the residual tensile strengths were found to slightly decrease as the exposure time increased. Overall the 8 hour exposure time produced at residual tensile strength of 90%, 60%, 41%, 32% and 29% at respective temperatures of 752°F (400 °C), 932°F (500 °C), 1112°F

(600 °C), 1300°F (704 °C) and 1589°F (865 °C). Despite the extended exposure time, residual tensile strengths were approximately 40% higher than that of specimens tested at their respective elevated temperature.

Neves *et al.* heated a single wire which was cut from the center of the seven-wire prestressing strand. Temperatures examined were in increments of 212°F (100 °C) from 392°F-1652°F (200 °C-900 °C). The specimens were held at their designated temperature for 60 minutes and then were cooled one of two ways, naturally in the furnace with the door opened or immediate immersion in a vessel containing water. The behavior of the tensile strength of the strands initially decreased as reported by Abrams and Guyon. However, at 1472°F (800 °C) Neves[8] reported an increase in tensile strength of 8 percent for the specimens cooled naturally in the furnace and an increase of 20% for the specimens cooled by water. This result is quite different from that reported by Abrams and Guyon. Neves proposed the increase in tensile strength was due to the differences in steel composition.

A recent study performed by MacLean[7] replicated the procedure of Abrams and Neves' previous research. MacLean tested single wires cut from the center of seven-wire, lowrelaxation prestressing strands. The wires were heated to temperature increments of 212°F (100 °C) from 392°F-1652°F (200 °C-700 °C) and a control 68°F (20 °C) and then were held at their designated temperature for 90 minutes. The specimens were then left in the furnace to cool. The results obtained were consistent with Abrams and Guyon. Based on the experimental data and data previously published Equation 1 was proposed as a method of determining the residual tensile strength of prestressing strands based on temperature, where T is in degrees Celsius and fu is the ratio of the ultimate tensile strength at a given temperature T, to the ultimate tensile strength at 68ºF (20 ºC).

$$f_u(T) = 0.25 + \frac{0.75}{1+(T/550)^{6.5}} \qquad ...(1)$$

A summary of the published residual tensile strength of prestressing strands collected from these various studies is shown in Figure 2. The notation NS, SR and LR refer to the type of strand. NS is for unspecified strands, SR is stress-relieved strands and LR is low-relaxation strands.

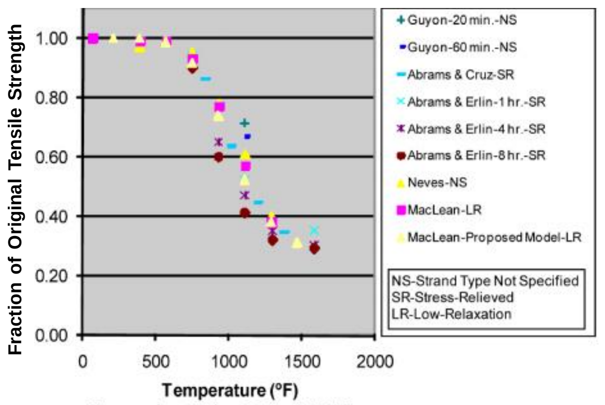
Modulus of Elasticity of Prestressing Strands

The modulus of elasticity was found to be independent of temperature by Holmes *et al.* and McLean. The modulus of elasticity property increased slightly as the temperature increased but then decreased back to the undamaged value near the end of testing.

RESEARCH PROGRAM

For Phase I of this experimental program tension tests were performed. The tests were performed after the strands had been exposed to different

Figure 2: Residual Tensile Strength of Prestressing Strands vs. Temperature



Conversion Units: 1ºF = 0.56ºC

levels of elevated temperature. The tension testing was used to analyze the tensile strength and stiffness properties of the prestressing strand after damage.

TENSION TESTS

Within the tension tests there were two phases of testing. Phase IA was designed to understand the tensile strength of the strand at elevated temperatures. It also considered effects due to the method of cooling. Phase IB of the experiment examined the tensile strength properties due to a shorter time of heat exposure (heat soak).

Test matrices for Phase IA and IB can be seen in Tables 1-4. The Specimen ID given in each table is given in the format of A-B-C-D, where the A designates the phase number, B designates the strand size, C specifies the temperature level and D gives the cooling method. The label B is used to designate strand size with “1” for 0.375 in. and “2” for 0.5 in. The C designation is given by numbers 1-6, which refer to the temperature levels beginning with the control as “1” and continuing up to 1300°F (704 °C) which is given as “6”. The D designation for the cooling method is denoted by “1” for cooling outside the furnace and “2” for cooling inside the furnace.

Phase IA

For the control, 500°F (260 °C) and 800°F (427 °C), three (3) coupons per strand size were heated and tested. These specimens were cooled by removing them from the furnace. For the higher temperatures, 1000°F (538 °C), 1200°F (649 °C), and 1300°F (704 °C), six (6) coupons were heated for the 0.5 in. diameter strands and four (4) were heated for the 0.375 in. diameter strands. The increase in number of strands was to observe the effects due cooling. Three (3) of the 0.5 in. and two (2) of the 0.375 in. were cooled inside the furnace and the remaining three (3) 0.5 in. and two (2) 0.375 in. were cooled by removing them from the furnace. All strands were held at their specific temperature for 60 minutes. This Phase IA length of soak time was consistent with previous studies[6,7].

Phase IB

In addition to Phase IA, additional testing was also performed where the specimens were held at their desired temperature for 35 minutes. The decrease in heat soak time was due to interest in

Table 1: Tension Test Matrix Phase IA: 0.375-in. Strand Diameter

Specimen ID	No. of Coupons	Temperature, °F (°C)	Heat Soak Time, min	Cooling Method
1-1-1-1	3	Control	60	Outside Furnace
1-1-2-1	3	500 (260)	60	Outside Furnace
1-1-3-1	3	800 (427)	60	Outside Furnace
1-1-4-1	2	1000 (538)	60	Outside Furnace
1-1-4-2	2	1000 (538)	60	Inside Furnace
1-1-5-1	2	1200 (649)	60	Outside Furnace
1-1-5-2	2	1200 (649)	60	Inside Furnace
1-1-6-1	2	1300 (704)	60	Outside Furnace
1-1-6-2	2	1300 (704)	60	Inside Furnace

Table 2: Tension Test Matrix Phase IA: 0.5-in. Strand Diameter

Specimen ID	No. of Coupons	Temperature, °F (°C)	Heat Soak Time, min	Cooling Method
1-2-1-1	3	Control	60	Outside Furnace
1-2-2-1	3	500 (260)	60	Outside Furnace
1-2-3-1	3	800 (427)	60	Outside Furnace
1-2-4-1	3	1000 (538)	60	Outside Furnace
1-2-4-2	3	1000 (538)	60	Inside Furnace
1-2-5-1	3	1200 (649)	60	Outside Furnace
1-2-5-2	3	1200 (649)	60	Inside Furnace
1-2-6-1	3	1300 (704)	60	Outside Furnace
1-2-6-2	3	1300 (704)	60	Inside Furnace

Table 3: Tension Test Matrix Phase IB: 0.375-in. Strand Diameter

Specimen ID	No. of Coupons	Temperature, °F (°C)	Heat Soak Time, min	Cooling Method
2-1-4-1	3	1000 (538)	35	Outside Furnace
2-1-5-1	3	1200 (649)	35	Outside Furnace
2-1-6-1	3	1300 (704)	35	Outside Furnace

Table 4: Tension Test Matrix Phase IB: 0.5-in. Strand Diameter

Specimen ID	No. of Coupons	Temperature, °F (°C)	Heat Soak Time, min	Cooling Method
2-2-4-1	3	1000 (538)	35	Outside Furnace
2-2-5-1	3	1200 (649)	35	Outside Furnace
2-2-6-1	3	1300 (704)	35	Outside Furnace

the materials properties for specimens exposed to elevated temperatures for shorter periods of time (i.e., more rapid emergency response). This also raises the question of whether a 60 minute soak time would appropriately address long duration fires. This issue is addressed in greater detail in Phase III of this study.

For Phase IB, three (3) temperatures were studied, 1000°F (538 °C), 1200°F (649 °C) and 1300°F (704 °C). Three (3) strands per temperature were tested for both the 0.5 in. and 0.375 in. size strands. The specimens were removed from the furnace and cooled naturally.

MATERIALS

Prestressing Strands

The specimens selected for the experiment were uncoated seven-wire low-relaxation prestressing strands of grade 270 ksi (1862 MPa). Two (2) sizes of wires were used, 0.5 in. (12.7 mm) and 0.375 in. (9.53 mm) diameter, with cross-sectional areas of 0.153 in^2 and 0.085 in^2 respectively. ASTM A 416/A 416M-06 provides

Table 5: Mechanical Properties of Prestressing Strands

	Area, in^2 (mm^2)	Yield Stress, ksi (MPa)	Fracture Stress, ksi (MPa)	Minimum Fracture Strength, lbf (kN)	Modulus of Elasticity, ksi (MPa)
0.5 in.	0.153 (12.7)	243 (1675)	270 (1862)	41,300 (183.7)	28,500 (196,500)
0.375 in.	0.085 (9.53)	243 (1675)	270 (1860)	23,000 (102.3)	28,500 (196,500)

required properties for this type of prestressing strand as illustrated in Table 5. In order for a strand to be acceptable for use in construction and certified by its supplier the yield stress and minimum fracture strength must be met. These values are also used to verify testing procedures used in experimental research.

DESCRIPTION OF TEST SPECIMENS

The coupon specimens were cut into lengths of 18 in. (457.2 mm), a value based on ASTM A416M-06, the grip length of the jaws, and the furnace dimensions. Nothing additional was applied or performed on the prestressing strands prior to exposure to elevated temperatures. A schematic and actual view of the specimen is given in Figure 3.

TEST SETUP

Furnace

In order to simulate fire damage, the specimens were placed inside a cylindrical tube furnace and heated to their designated temperature at a rate of approximately 8°F/min (4.4 °C/min). The temperature was measured using a thermocouple which was directly linked to the temperature controller.

For the first set of coupons, the temperature was increased until it reached its designated value and then held for 60 minutes, allowing a uniform temperature to be reached. The specimens that were to be cooled outside the furnace were then removed, placed at room temperature and allowed to cool. The furnace was turned off and the remaining specimens were left in furnace and cooled as the furnace naturally cooled down. The second set of coupons were heated in the same manner, but only held at their specific temperature for 35 minutes. They were cooled outside the furnace after their heat soak was completed. As previously noted, the heat soak time period of 60 minutes was based on previous research[6,7] and the 35 minute period was chosen to research the effects caused by a shorter period of exposure time.

Figure 3: Schematic and Actual View of Coupon Specimens

When heating the coupon specimens, all replicate specimens for each condition were placed in the furnace at the same time. The furnace and heating setup can be seen in Figures 4 and 5. The white blocks shown in Figure 5 were oven bricks which were used elevate the coupon specimens in the furnace and keep them from touching one another during heating.

Figure 4: Cylindrical Tube Furnace

Figure 5: Typical Heating Setup

Testing Equipment and Procedures

Tensile testing was performed using a MTS880 machine as shown in Figure 6. Load, strain, and stroke were electronically recorded for each specimen. In order to achieve equal grip strength around the strands, a 3 in. (76.2 mm) long aluminum tube made of aluminum alloy 6061 with a thickness of 0.049 in. was placed on both ends of the coupon. For the 0.5 in. dia. strands a 0.625 in. (15.88) outside diameter, 0.527 in. (13.39 mm) inside diameter aluminum tube was used. The 0.375 in. dia. strands employed a 0.5 in. (12.7 mm) outside diameter, 0.402 in. (10.21 mm) inside diameter aluminum tube. This allowed the grips to squeeze the aluminum into the gaps between the individual wires and prevent slipping or premature fracture. A small weld was also placed at the ends of each specimen to ensure the strands were loaded uniformly. Gripping strength was set at 7.5 ksi (51.8 MPa) for the 0.5 in. specimens and 6 ksi (41.4 MPa) for the 0.375 in. specimens. A typical specimen placed in the MTS880 machine can be seen in Figure 7.

Figure 6: MTS880 Testing Machine Prior to Tension Tests

Figure 7: Tension Test Setup

The procedure for the coupon testing began by centering the specimen inside the testing machine. The specimen was loaded to an initial load of 10% of the minimum breaking strength as specified by ASTM A416M-06 and ASTM A370-07a. A Class-C extensometer was then placed on the strand and the gauge reading was set to 0.001 in./in. (0.0254 mm/mm). Loading rates for each strand diameter were selected to be 23% of the maximum acceptable load set by ASTM A370-07a. These values were based on the standard's allowable range and testing machine's capabilities. Initial loads and load rates can be seen in Table 6.

Table 6: Testing Properties of Prestressing Strands

Strand Diameter in. (mm)	Initial Load lbf (kN)	Loading Rate lbs/min (kN/min)
0.5 (12.7)	4,130 (18.4)	3,470 (15.44)
0.375 (9.5)	2,300 (10.2)	1,930 (8.59)

Loading continued until yielding took place. The extensometer was then removed in order to prevent damage to itself during fracture. For specimens unexposed to the furnace the yield was taken at an elongation of 1% which was recorded by the machine as a strain value of 0.01 in./in. (0.254 mm/mm) in accordance with ASTM A416M-06. For the heat-exposed specimens yield occurred much sooner and the extensometer was removed once the curve on the computer clearly changed slope signifying a yield. During and after the removal of the extensometer, the loading continued and was completed when the specimen fractured. For certain cases, particularly the higher temperatures, a clear change in slope was not recognizable and therefore the extensometer was left on the specimen until failure.

EXPERIMENTAL TEST RESULTS

Visual Observations

Visual observations of the prestressing strands were made prior to testing and are presented in Figures 8-12. Noticeable changes to the strand's appearance were first observed with the specimens exposed to 1000°F (538 ºC). These coupons' shiny appearance was replaced by a dark dull appearance which indicates the beginning of steel oxidation. The strands heated to 1200°F (649 °C) were also found to be dull and in addition their exterior coating began to slightly flake off. Finally the specimens of 1300°F (704 °C) showed significant flaking of the exterior and dullness. The discolored areas in Figure 12 are parts of the strand where the exterior flaked off after heating during transport. Coupons exposed to 500°F (260 °C) and 800°F (427 °C) remained cosmetically the same as they were

Figure 8: Strand After Exposure to 500°F (260 °C)

Figure 9: Strand After Exposure to 800°F (427 °C)

Figure 10: Strand After Exposure to 1000°F (538 °C)

Figure 11: Strand After Exposure to 1200°F (649 °C)

Figure 12: Strand after Exposure to 1300°F (704 °C)

prior to heating, with an exterior characterized by a shiny appearance. These observations were the same for each temperature regardless of the type of cooling method or length of heat soak.

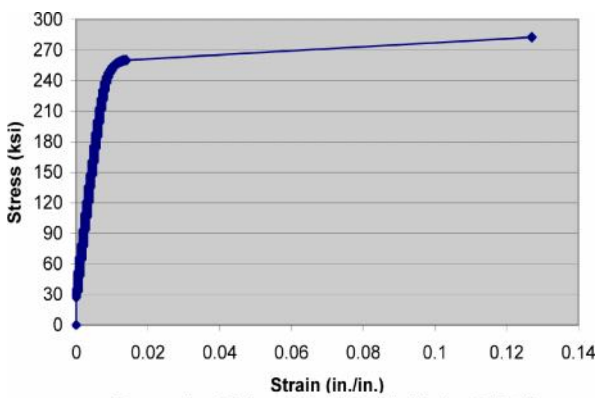
Test Results

The results of the tension tests are presented in this section. For each of the tests, stroke and load were recorded for the entire loading period. Strain was recorded until at least the yield point as discussed earlier. A typical stress-strain plot produced by a tension test is shown in Figure 13. Moore and Myers[1] report the yield stress, the ultimate load, the modulus of elasticity as well as the standard deviation for each replicate and condition of three previously mentioned properties.

Failure Mode

The failure modes of the strands were directly related to the heat damage experienced in the furnace. As the exposure temperature increased, the failure mode moved closer to the lower grip where the machine was elongating the strand. Due to the irregular shape of prestressing strands this type of failure is considered acceptable by ASTM A370-07a.

Figure 13: Typical Stress-Strain Curve for Tension Testing



Conversion Units: 1°F = 0.56°C; 1 ksi = 6.9 MPa

Specimens exposed to elevated temperatures were not expected to meet mechanical property ASTM requirements due to mechanical alterations by heat, however unexposed strands were used to verify acceptance of the testing method. These specimens failed in an acceptable manner stated by ASTM A370-07a by producing a yield greater than 243 ksi (1675 MPa) and a breaking strength greater than 270 ksi (1862 MPa). These specimens also failed in the center between the two jaws. Typical failure modes are shown in Figure 14.

TENSILE STRENGTH

From the test results several important observations can be made. Tensile strength, modulus of elasticity and yield strength are all specific properties which have been analyzed and reported in this section. Additional analysis and conclusions have been made regarding temperature level, size of strand, cooling method and heat exposure time.

Figure 14: Typical Failure Mode of Prestressing Strand in Tension

The percent of original tensile strength vs. temperature for the specimens of Phase IA (heated for 60 minutes) can be seen in Figure 15. The tensile strength of the strands decreases by only 4% for the 0.5 in. strands and 1% for the 0.375 in. strands between the temperatures of 68°F (20 °C) and 500°F (260 °C). A slightly larger weakening occurs between the temperatures of 500°F (260 °C) and 800°F (427 °C) as there is an 8% and 11% decrease for the 0.5 in. and 0.375 in. strands, respectively. However, a significant loss in tensile strength occurs after 800°F (427 °C). The curve begins a steep downward trend until it reaches 1200°F (649 °C) where it starts to level off. For temperatures 800°F (427 °C) to 1200°F (649 °C) a total loss of 48% and 46% was experienced by the 0.5 in. and 0.375 in. strands respectively.

Based on Figure 15 it appears that the loss of tensile strength is proportional for both strand sizes. There is a small statistical difference between the strands sizes in the percent of ultimate tensile strength at 500°F (260 °C), 1000ºF (538 ºC) and 1200°F (649 °C). However, there is no indication that the size of the steel has any effect on the residual tensile strength of the steel,

Figure 15: Residual Ultimate Tensile Strength vs. Temperature

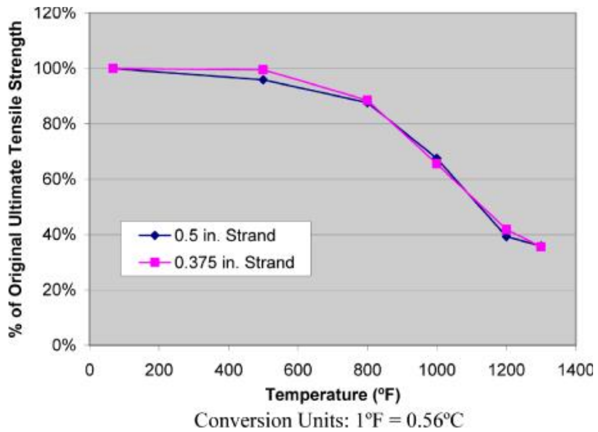
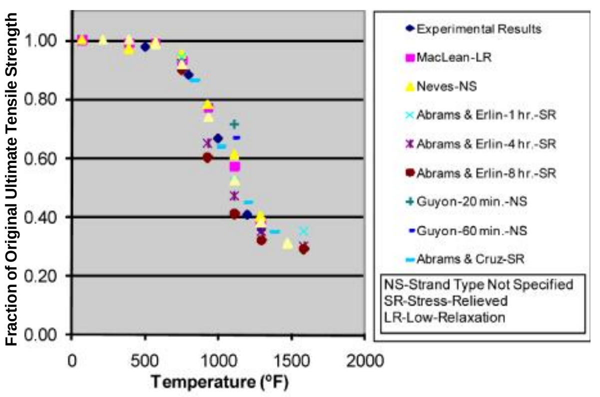
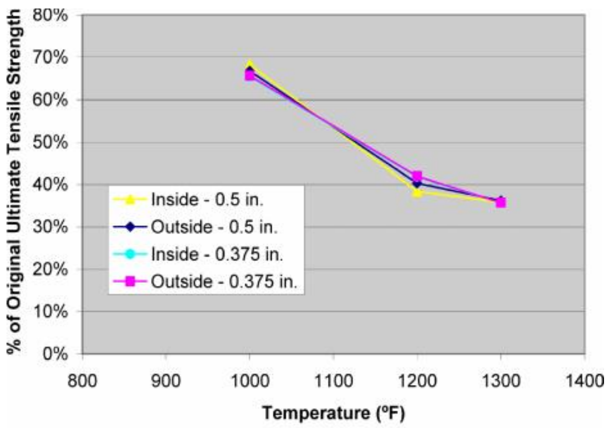


Figure 16: Comparison of Results with Other Previous Research



Conversion Units: 1°F = 0.56°C

Figure 17: Comparison of Cooling Methods



Conversion Units: 1°F = 0.56°C

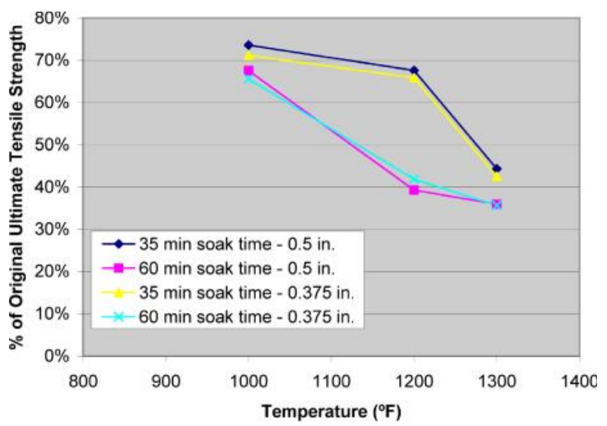
because the strand with the highest residual tensile strength varied by temperature. If there was an increase in the specimen pool size it is likely that a statistical difference would not exist.

All data obtained from this study and previous studies has been reprinted in Figure 16 with the addition of the experimental results from Phase IA of this study. The current results are quite similar to that of previous research and can be assumed to be accurate.

Figure 17 compares the ultimate tensile strength of the strands which were left to cool inside the furnace (i.e., more gradually) and those which were removed and cooled outside of the furnace. Statistically there is a small difference between strands cooled inside the furnace and strands cooled outside of the furnace. The standard deviation for various replicate testing for each conditioning ranged from 0.10-0.87% and 0.54-3.13% for the 0.375 and 0.50 in. strands respectively.

The length of heat soak time is shown in Figure 18. At higher temperatures there is a greater loss in strength for specimens soaked for 60 minutes versus those only soaked for 35 minutes. For temperatures between 1000°F (538 °C) and

Figure 18: Comparison of Heat Soak Time



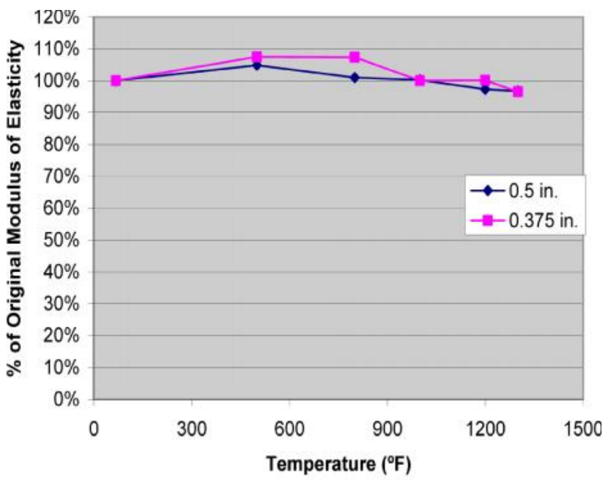
Conversion Units: 1°F = 0.56°C

1300°F (704 °C), it appears to be more significant than the lower temperatures. However, there is still a measurable difference in strength loss. The data obtained for the specimens soaked for 35 minutes is similar to that of Guyon[4] who soaked specimens for 20 minutes. However, Guyon did not report the type of strand tested; therefore no direct correlation can be made. Abrams and Erlin[6] also noted a difference in tensile strength due to the length of time the specimens were soaked. However, their study consisted of longer time intervals (1 hour, 4 hours and 8 hours) which resulted in small variances.

MODULUS OF ELASTICITY

The modulus of elasticity based on temperature exposure is given in Figure 19. The values for this property were determined by measuring the slope of the initial linear section of the plot. This particular property was found to be fairly constant despite the increase in temperature. The values actually increased for temperatures of 500°F (260 °C) and 800°F (427 °C). They then decreased for the remaining elevated temperatures, but only to 97% of the original modulus value. This compares similarly to MacLean8 and Holmes[9]. The behavior of the prestressing strand is much like that of mild steel which has also been found to not change after heating and cooling[3].

Figure 19: Residual Modulus of Elasticity



Conversion Units: 1°F = 0.56°C

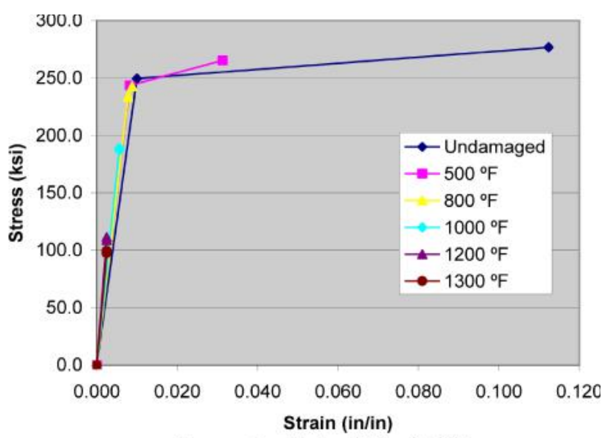
YIELD STRENGTH

As defined by ASTM A416M-06, the yield strength is taken at 1 percent elongation. However, for the specimens exposed to elevated temperatures, this elongation was not possible and the yield was taken at the point of significant slope change. Furthermore, for very high temperature specimens, yield strength was often unrecognizable as fracture occurred before any slope change occurred.

In the case of the 0.5 in. dia. strand heated to 800ºF (427 ºC), the fracture occurred immediately after the yield with little tensile strength increase. Strands heated to temperatures above 800ºF (427 ºC) fractured before an indication of yielding occurred. The 800ºF (427 ºC) temperature mark is very close to the limit at which all non-linear behavior is lost. You will note from the stress-strain curves shown in Figures 20-21, that the 0.375 in. strand heated to 800ºF (427 ºC) did exhibit some non-linearality, but at 1000ºF (538 ºC) did not exhibit any. Therefore, the temperatures of 800ºF-1000ºF (427 ºC-538 ºC) are a critical temperature range for the strands in which all non-linear behavior is lost.

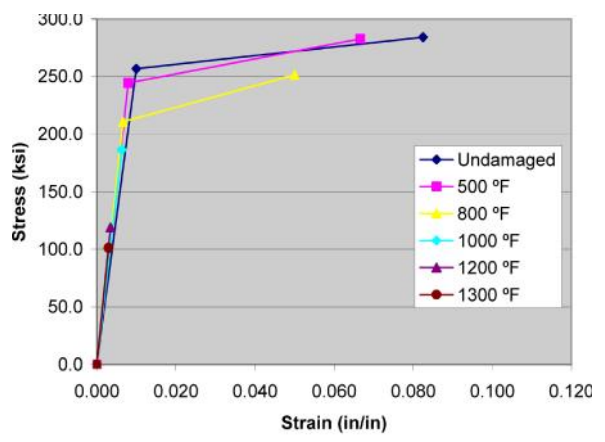
The loss of non-linear behavior is directly related to the loss of ductility and prior indication of failure. Strands heated to the 800ºF-1000ºF (427 ºC-538 ºC) temperature range will still maintain over 65% of their undamaged tensile strength which in some applications will be sufficient. However, in addition they will also lose almost or all of their non-linear behavior becoming

Figure 20: Stress vs. Strain for 0.5 in. Specimens of Phase I



Conversion Units: 1°F = 0.56°C

Figure 21: Stress vs. Strain for 0.375 in. Specimens of Phase I



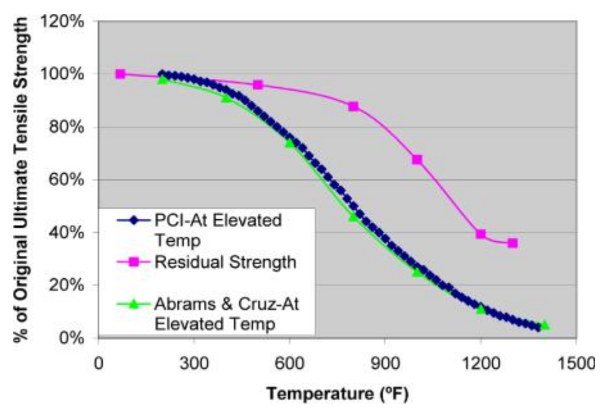
Conversion Units: 1°F = 0.56°C

more brittle. Materials which fail without significant warning are normally avoided for use in structural components. Some sign of distress such as significant concrete cracking prior to failure is desirable, which means the loss of ductility in the reinforcing is highly undesirable.

TENSILE STRENGTH AT ELEVATED TEMPERATURES

Another topic of interest is how the residual tensile strength of the strands compares with the tensile

Figure 22: Comparison of Tensile Strength for Prestressing Strands at Elevated Temperatures and Residual Tensile Strength of Prestressing Strands



Conversion Units: 1°F = 0.56°C

strength of the strands at elevated temperatures. In Figure 22, the experimental results from this study are compared with the tensile strength of prestressing strands at elevated temperatures reported by other researchers[5,10]. It can be noted that there is a significant increase in tensile strength upon cooling for all temperatures greater than 400ºF (204 ºC).

CONCLUSION

Prestressing strand properties were evaluated after exposure to temperatures ranging between 68°F (20 °C) to 1300°F (704 °C) and then cooled either inside or outside the furnace. Exposure time periods analyzed included 35 minutes and 60 minutes of soak time in the furnace. Properties were determined by tension testing of the strands. Based on the experimental data, the following conclusions can be drawn:

1. There is significant loss in prestressing strand tensile strength upon exposure to elevated temperatures greater than 500ºF (260 ºC). This significant loss for the increment of 500ºF-800ºF (260 ºC-427 ºC) is 9.6% and increases to 21.5 and 26.0% for respective temperatures increments between 800ºF-1000ºF (427 ºC-538 ºC) and 1000ºF-1200ºF (538 ºC-649 °C). The final temperature range, 1200ºF-1300ºF (649 °C-704 ºC), which is the smallest increment, experienced a tensile strength loss of 4.8%. A minimal tensile strength loss of 2.3% occurred at the initial temperature increment of 68ºF-500ºF (20 ºC-260 ºC).

2. The duration of exposure to elevated temperatures is critical in the residual tensile strength after cooling. Strands soaked at a temperature for 35 minutes performed better than those soaked for 60 minutes. A significant difference in performance of 6-25% was found

for temperatures 1000ºF-1300ºF (538 ºC-704 ºC).

3. Regardless of the cooling method employed in this study the prestressing strands behaved similarly.
4. The soak or exposure time investigated in this study (35 and 60 minutes) did exhibit measurable differences in the tensile properties.
5. The modulus of elasticity post-conditioning was largely unaffected by the exposure temperature.
6. The non-linear behavior of the prestressing steel is significantly affected upon reaching the critical temperature range of 800ºF-1000ºF (427 ºC-538 ºC). Within these temperatures the steel becomes brittle, yielding at fracture or fracturing before yielding depending on the temperature exposure.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support of the Center for Transportation Infrastructure and Safety (CTIS) at the Missouri University of Science and Technology (Missouri S&T). Coreslab Structures, Inc. of Marshall Missouri is greatly acknowledged for their contributions of prestressing tendon for the study. Thanks are also due to the Materials Research Laboratory (MRC) at Missouri S&T for assistance and usage of their high temperature furnace. The technician and staff support from the Center for Infrastructure Engineering Studies (CIES) and Department of Civil, Architectural, and Environmental Engineering at the Missouri University of Science and Technology has also provided much appreciated assistance.

REFERENCES

1. Abrams M S and Cruz C R (1961), "Behavior of High Temperatures of Steel Strand for Prestressed Concrete", *Journal of the PCA Research*, Vol. 3, No. 3, pp. 8-19.
2. Abrams M S and Erlin B (1967), "Estimating Post-Fire Strength and Exposure Temperature of Prestressting Steel by Metallographic Method", *Journal of the PCA Research*, Vol. 9, No. 3, pp. 23-33.
3. Dias W P S (1992), "Some Properties of Hardened Cement Paste and Reinforcing Bars Upon Cooling from Elevated Temperatures", *Fire and Materials*, Vol. 16, No. 1, pp. 29-35.
4. Edwards W T and Gamble W L (1986), "Strength of Grade 60 Reinforcing Bars After Exposure to Fire Temperatures", *Concrete International: Design & Construction*, Vol. 8, No. 10, pp. 17-19.
5. Guyon Y (1953), *Prestressed Concrete*, F.J. Parsons, Folkestone and Hastings, Limited of London, London.
6. Holmes M, Anchor R D, Cook G M E and Crook R N (1982), "The Effect of Elevated Temperatures on the Strength Properties of Reinforcing and Prestressing Steels", *The Structural Engineer*, Vol. 60B, No. 1, pp. 7-13.
7. MacLean K (2007), "Post-Fire Assessment of Unbonded Post-Tensioned Concrete Slabs: Strand Deterioration and Prestress Loss", Masters of Science Thesis, Department of Civil Engineering, Queen's University, Kingston, Ontario, Canada.
8. Moore W L and Myers J J (2008), "Performance of Fire-Damaged Prestressed

Concrete Bridges", p. 139, Missouri University of Science and Technology.

9. Neves I C, Rodrigues J P and Loureiro A (1996), "Mechanical Properties of Reinforcing and Prestressing Steels After Heating", *Journal of Materials in Civil Engineering*, pp. 189-194.

10. Precast/Prestressed Concrete Institute (PCI), (2004), *PCI Design Handbook*, 6th Edition.