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MICROSTRUCTURAL AND MECHANICAL CHARACTERISATION OF POST-TENTIONING STRANDS FOLLOWING ELEVATED TEMPERATURE EXPOSURE

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Abstract

Prestressing strands lose strength and become more susceptible to creep deformation when they are heated during a fire. The consequent loss in prestressing force could under certain conditions result in structural collapse, potentially outwith the heated region of the structure. This paper describes a test programme characterising the changes in microstructure of steel prestressing tendons exposed to elevated temperatures. The residual strength tests, hardness testing, and elevated temperature mechanical test were performed to demonstrate how recovery and recrystallisation of the initially work-hardened steel produce changes in its mechanical properties at elevated temperatures. The research results of this paper are beneficial not only in the fire design of post-tensioned structures using modern prestressing steel, but also in the assessment of the tendons' residual strength after being affected by fire.

Keywords: Prestressing steel, microstructure, hardness, residual strength, creep.

1 INTRODUCTION

The prestressing tendons used in pre-tensioned and post-tensioned concrete construction can be greatly affected by elevated temperature, potentially resulting in catastrophic collapse of a structure. Even if collapse does not occur, heating can reduce both the strength of the tendon at elevated temperature, and the residual strength after it has cooled down, and the tendon can undergo creep deformation. The extent of damage is often not visually quantifiable and another means of assessment must therefore be sought.

This paper reports a study of the changes in physical and mechanical properties of a modern prestressing steel at high temperatures. It examines how the microstructure, hardness and residual tensile strength of the steel is affected by temperature. The aims are to (a) provide fundamental information on the behaviour of prestressing steel subjected to fire temperatures, and to (b) allow the post-fire condition of a tendon to be assessed by means of a simple, cheap, and non-destructive hardness test.

1.1 Previous Work Characterising the Effect of Temperature upon Prestressing Steel

The tendons in pre- or post-tensioned concrete are embedded in concrete that provides good insulation; however it is possible for the tendon to reach temperatures over 400°C, and well above this temperature if the tendon or the tendon duct are exposed directly to fire following spalling or cracking of the cover concrete (Gales *et al.*, 2011).

The strength of prestressing steel decreases significantly when exposed to temperatures above 300°C (Holmes *et al.* 1982; Neves *et al.*, 1996; Maclean, 2007), and can loose 50% of its strength at high temperatures. Preloading the strands prior to testing makes little difference to its behaviour. There is a slight increase in strength, however, for temperatures above 700°C (Abram & Erlin, 1967; Holmes *et al.,* 1982).

The mechanical performance of prestressing steel follows from the changes in microstructure that occur as it is heated. Prestressing steel is a cold-drawn, pearlitic steel (a eutectoid mixture of iron carbide and ferrite). At ambient temperature its microstructure consists of thin, elongated pearlite grains. Between 400°C and 700°C, spheroidisation occurs (in which the iron carbide in the pearlite forms globules), accompanied by recovery (in which the dislocations present due to cold working are annihilated). Upon heating to temperatures above 700°C, the matrix recrystallises completely and forms new grains, which then grow over time (Abrams & Erlin, 1967).

A correlation between hardness, tensile strength, microstructure and temperature was established for prestressing steel in the 1960s by Abrams & Erlin (1967). Modern steel, however, has a different chemical composition; the composition of the prestressing steel studied in this paper is compared to those used in previous studies in Tab. 1. The current BS 5896 steel has a higher carbon content and a lower phosphorus and sulphur content than the steel tested by Abrams & Erlin. Gales *et al.* (2012) have identified that existing design guidance may overestimate creep deformation, as a result of the changes in the steel used for prestressing tendons. Consequently, the design guidance may be non-conservative for predicting tendon rupture during a fire, and it is important to re-examine the performance of prestressing steels at high temperatures.

Tab. 1 Carbon and main alloy content in the steels used in previous and current studies

	C (%)	Mn (%)	P (%)	S (%)	Si (%)
Abrams & Erlin (1967)	0.794	0.498	0.0118	0.0376	0.288
Neves *et al.* (1996)	0.824	0.712	0.02	0.013	0.235
MacLean (2007)	0.80	0.868	0.023	0.012	0.45
Current Tests (BS 5896, 2000)	0.90	0.66	0.007	0.014	0.25

2 PROCEDURE

The tests were performed on prestressing steel strands and core wires made to British Standard BS 5896 (2000). The hardness, residual strength and microstructure of the steel were studied after cooling.

2.1 Heat Treatment

Unloaded and unrestrained strands were heated to temperatures of 200, 400, 500, 600, 700 and 800°C. Two samples were tested for each exposure temperature. The samples were placed in a furnace and heated from room temperature to the target temperature at 10°C/min, using four thermocouples to monitor the furnace and sample temperatures. The specimens were then held at the target temperature for 1.5 hours, followed by air-cooling to simulate natural cooling following a fire. This heating regime matched previous tests by MacLean (2007).

An additional four samples were heated to 400°C and held for periods of 4 and 8 hours (corresponding to the study by Abrams & Erlin, 1967). These samples allowed the effect of soak time upon microstructure and hardness to be studied at 400°C, for which significant changes in mechanical properties start to occur (Neves *et al.*, 1996; MacLean, 2007; Myers & Bailey, 2009).

2.2 Hardness

Vickers hardness tests were performed on all the heated core wires. 30 mm long samples were ground using P400 silicon carbide paper to produce a flat, clean surface at least 2 mm wide. The samples were mounted in a special stand, tested under the equivalent of a 30kg mass, and the appropriate conversion used to obtain the Diamond Pyramid Hardness (DPH) value. Four hardness tests were performed in the centre of each sample (to eliminate the influence of the sample edges) and the results were averaged.

2.3 Microstructure

Microstructural observation of both transverse and longitudinal sections of the samples were conducted through a Zeiss Axioscope light microscope. Two 10 mm long sections were cut from each sample and mounted in EpoxiCure resin. These were ground using gradually finer grit paper and then polished with cloths and diamond paste, to obtain a flat, scratch-free surface. The samples were etched with 2% Nital to expose the grain structure.

2.4 Residual Tensile Strength

Residual tensile strength tests were performed on the core wires after cooling using an Instron 600LX universal testing machine. The samples were tested using a free length of 50 mm, at a strain rate of 2 mm/min (to avoid creep effects). Digital Image Correlation (DIC) was used to measure the steel strains during the tests (see Gales *et al.* (2012) for details).

2.5 Tension test

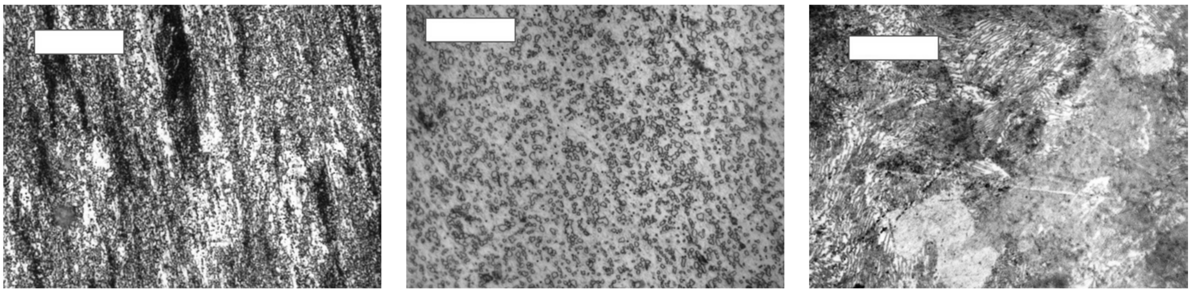
The core wire from a prestressing strand was heated at 10°C/min to a temperature of 500°C and held for 15 mins. The sample was loaded at 1mm/min whilst maintaining the temperature at 500°C. The test was stopped before failure to observe necking, which occurred in two distinct places. The necked sections were tested for hardness and prepared for microscopy as described above.

3 RESULTS AND DISCUSSION

The results obtained during this study are compared with prior research by Abrams & Erlin (1967), Holmes (1982), Neves (1996), MacLean (2007), and Myers & Bailey (2009). These authors studied the change in residual mechanical and material properties of loaded and/or unloaded prestressing steel samples with temperature.

3.1 Microstructure

(a) Ambient temperature (b) 400°C, 1.5h soak (c) 400°C, 8h soak



(d) 600°C, 1.5h soak (e) 700°C, 1.5h soak (f) 800°C, 1.5h soak

Fig. 1 Longitudinal sections for different exposure temperatures and times; the length bar is 20 μm long.

Fig. 1 shows the microstructure of the longitudinal sections at different temperatures and soak times. The elongated pearlite grains are clearly shown in the non-heated prestressing steel (Fig. 1a). The extensive cold-drawing during manufacture of the steel wire results in very fine grains that cannot be distinguished in the transverse direction.

A similar microstructure with long, fine grains is evident for samples that have been heated up to 500°C (Fig. 1b and 1c), and it is not possible resolve the individual grains in the transverse view. However, the pearlitic banding is less clear in the 400°C samples. Whilst (even at 1000× magnification) it was difficult to discern this banding, it is possible to see that the proportion of pearlitic banding was lower. For the 8h soak time, the original structure is still visible, but the clear pearlitic structure has disappeared and slightly grainier dark and light bands are visible. This suggests that the effect of this temperature upon the steel is time dependent.

For temperatures above 500°C pearlite starts to dissociate into ferrite and globular iron carbide, and the microstructure is a mixture of the pearlite grain structure and the new globular structure. This is evident at 600°C in both longitudinal (Fig. 1d) and transverse directions.

At temperatures above 700°C the directionality of the original grain structure is lost. Above the eutectoid temperature (≈727°C), the steel transforms to austenite, but re-forms into coarse pearlite colonies upon cooling (Fig. 1e and 1f). Decarburisation is also observed for these temperatures; after heating, the samples were coated in a carbon layer and the proportions of ferrite in the microstructure near the surface were higher.

Similar trends were observed by Abrams & Erlin, Neves *et al.* and MacLean, despite the different compositions of the steels that they tested (Tab. 1).

3.2 Hardness vs. Temperature

The results from the Vickers hardness tests are shown in Fig. 2, which plots the reduction in hardness with exposure temperature.

There is no significant change in hardness for temperatures up to 300°C, with a marked decrease in hardness above 400°C. A minimum hardness (equal to 40% of the un-heated hardness) occurs for steel heated to 700°C. At 800°C, the hardness increases slightly (to 60%) due to recrystallization. These results correlate with those obtained by Abrams & Erlin (1967).

The multiple points at 400°C in Fig. 2 are due to the soak times of 1.5, 4 and 8h. The longest exposure resulted in the lowest hardness value, with a difference of not more than 8% (55 DPH) between the longest and shortest exposure times.

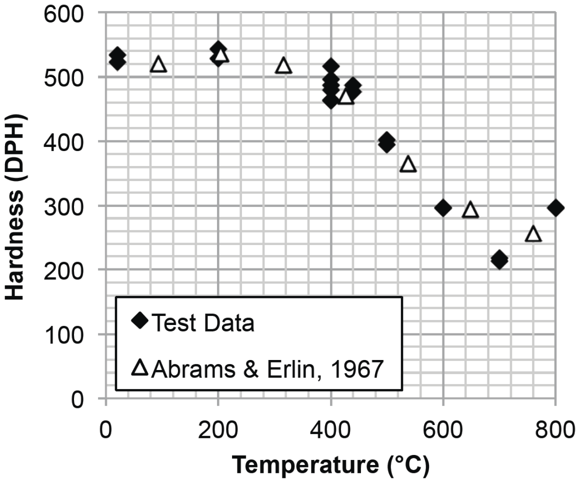


Fig. 2 Hardness variation with temperature

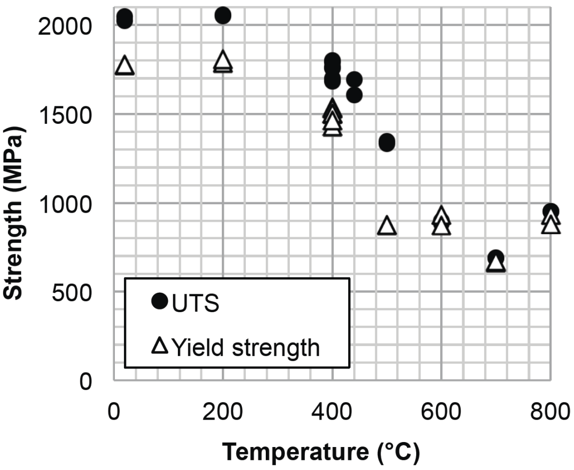


Fig. 3 Strength variation with temperature

3.3 Residual Strength vs. Temperature

Fig. 3 shows how the residual yield tensile strength and ultimate tensile strength (UTS) varied with exposure temperature. The yield strength was the stress at which the prestressing steel samples ceased to behave linearly. There is very strong similarity between Fig. 2 and 3, confirming the correlation between strength and hardness.

As with hardness, significant change in tensile strength occurs for temperatures below 300°C. The strength is reduced at 400°C, but neither the yield or ultimate tensile strengths are significantly affected by the exposure times at this temperature (the results are within 120MPa of each other). The minimum strength occurs at 700°C, where the UTS has reduced by nearly 70%, and the yield strength by around 60%. The strength recovers slightly at 800°C, with a residual UTS around 50% of the unheated strength.

Stress-strain curves were plotted using the DIC measurements of strain (but are not included here). The elastic portion of the response gave a Young's modulus (*E*) close to 210GPa, which is in the range defined by the manufacturer. The residual value of *E* did not vary significantly with exposure temperature. The stress-strain curves for the majority of the specimens had clear elastic-plastic regions with very little hardening. Those exposed to 800°C, however, were similar to those for mild steel, with hardening, a consequence of the un-worked microstructure of the steel following heating to 800°C (Fig. 1f).

Fig. 4 compares the UTS results from the present study (from Fig. 3) to the results from previous studies, normalised with respect to the unheated strength. The trend is the same as for previous work except for that of MacLean, who obtained higher residual UTS values for temperatures above 400°C. A recovery of residual UTS is also observed for 800 °C by Neves *et al.* and Abrams & Erlin.

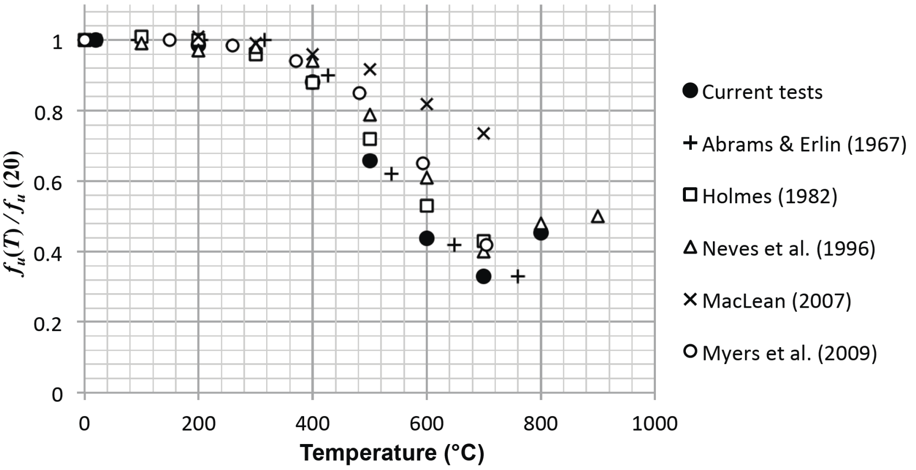


Fig. 4 Comparison of test data with previous studies

3.4 Heated Tension Test at 500°C

The strength test conducted at 500°C was used to determine whether loading at elevated temperature affects the hardness or microstructure of the steel (after it has been cooled). There was a small decrease in hardness of 8.3% compared to the unloaded sample. The loaded tests by Abrams & Erlin (1967) gave a similar result, which they deemed to be neglible, but it should be noted that the difference in hardness is similar in magnitude to that resulting from the different exposure times at 400°C.

The microstructure of samples taken from the necked region was similar to that of unloaded test, although the plastic deformation would have caused the formation of microcavities in the necked region.

3.4 Hardness as an Assessment of Residual Strength

The results demonstrate that the hardness of the modern prestressing steel (to BS 5896) correlates very well with the residual UTS, in a similar manner to historic prestressing steel (Abrams & Erlin, 1967).

Portable hardness testing may allow the residual tensile strength of a post-tensioning tendon to be assessed following a fire without needing to recourse to destructive test methods that require samples of steel to be removed from the structure.

Care is required, due to the non-unique values of hardness that occur between 600°C and 800°C, because hardness testing cannot distinguish steel exposed to these two temperatures. The ductility of the 800°C exposed steel will be higher, but this would require microstructural examination or mechanical testing. It is unlikely, however, that prestressing tendons exposed to any temperature in the 600°C to 800°C could be retained because of the consequent large reduction in strength.

4 SUMMARY

This study has examined how exposure to elevated temperatures up to 800°C affects the microstructure, hardness, and residual tensile strength of a modern prestressing steel.

Whilst the chemical composition of the British Standard steel examined here differs from the prestressing steels examined in previous studies (from the 1960s onwards), its elevated temperature performance is similar. Residual strength loss occurs from 400°C, with a maximum ultimate tensile strength of 70% at 700°C. The exposure time does not greatly affect its residual properties.

The residual strength loss is accompanied by a reduction in the steel’s hardness, and this may allow hardness testing as a non-destructive method to establish the residual strength of a prestressing tendon following fire.

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