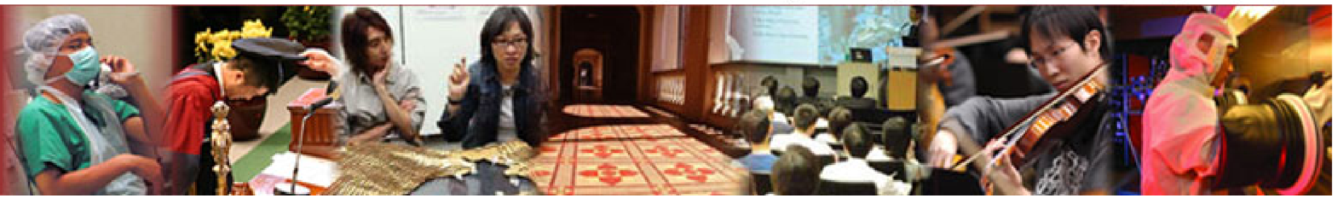

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MECHANICAL PROPERTIES OF PRESTRESSING STEEL AT ELEVATED TEMPERATURE AND AFTER COOLING

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ABSTRACT

The mechanical properties of prestressing steel at elevated temperatures and after cooling are essential to the fire resistance design and post-fire evaluation of residual load-carrying capacity of prestressed concrete structures. Although previous tests have provided useful results of mechanical properties of prestressing steel at elevated temperatures, the data obtained are somewhat scattered and still insufficient. Furthermore, few empirical formulas fitting the deterioration of prestressing steel at elevated temperatures and after cooling can be found.
This study therefore aims to extend the existing database with reliable data obtained by an accurate testing system. The study focuses on the mechanical properties of prestressing steel at elevated temperatures and after cooling by employing the central core wire of prestressing strand. Grade 1860 strands to GB/T5224 mostly used in Mainland China and Grade 1860 strands to BS5896 used in European countries are tested. The results are obtained using the steady-state method and compared with those from available literature and design standards. To help assess the residual load-carrying capacity of structures after fire and validate the representativeness of wire for strand behaviour, the mechanical properties of prestressing strands extracted from a few post-tensioned concrete flat slab specimens after fire testing are also investigated.

KEYWORDS

Cooling, elevated temperatures, fire, mechanical properties, prestressing strands.

INTRODUCTION

Prestressing steel plays a key role in prestressed concrete structures which are often used to achieve large span-to-depth ratios, economy and enhanced load-carrying capacity. However, degradation of mechanical properties occurs when prestressing steel is heated to temperatures above 300℃, leading to decrease of load-carrying capacity and potential collapse of structures. Extensive experimental investigations have been carried out on the mechanical properties of prestressing steel in fire (Li et al. 1998, Fan and Lü 2001, Fan and Lü 2002, Zheng et al. 2006, Zhou et al. 2008, Atienza and Elices 2009, Xin 2009, Wang et al. 2010, Gales et al. 2012). Although the elastic modulus of steel does not have substantial change after cooling down, the yield strength, ultimate strength and ductility will degrade depending on the peak temperature reached (Fan and Lü 2002, Fan 2004, Zheng et al. 2006,

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Atienza and Elices 2009). In the post-fire evaluation, it is important to determine the permanent damage and residual mechanical properties of the prestressing steel after cooling down to ambient temperature. Empirical formulas fitting the deterioration have been put forward by researchers based on existing test data (Fan 2004, Hertz 2004, Xin 2009, Wang et al. 2010).

EXPERIMENTAL INVESTIGATION

Test Specimen

Two different sets of 7-wire strands were used in the tensile tests, including Grade 1860 steel to GB/T5224 extensively used in Mainland China and Grade 1860 steel to BS 5896 widely used in European countries. The specimens tested were the core wires extracted from strands. The dimensions and chemical compositions are presented in Table 1.

Table 1. Dimensions and chemical composition of specimens

Dimensions and modulus	GB/T5224	BS 5896	Element	GB/T5224	BS 5896
Core wire diameter (mm)	4.35	5.39	Cr (%)	-	0.13
Core wire area (mm^2)	14.86	22.82	Mn (%)	0.73	0.74
Density (kg/m^3)	7800	7800	Si (%)	0.2	0.41
Total length (mm)	800	800	P (%)	0.015	< 0.01
Gripping length (mm)	150	150	C (%)	0.8	0.8
Clear length (mm)	650	650	S (%)	0.008	0.016
Nominal Young’s modulus (GPa)	200	204.1			

Test Equipment

Tensile test of prestressing wire in and after fire

The tensile testing machine used was MTS 810 Material Testing System of 250kN capacity. The heating device was MTS 653 High-Temperature Furnace with 3 heating chambers and a maximum temperature of 1400℃. The furnace was placed at the middle of specimen so that the heating length was 185mm. The furnace was monitored and controlled by an MTS model 409.83 temperature controller. The strain of the heated part of the specimen was measured by an MTS 632.54F-11 Axial Extensometer for High-Temperature Testing with Induction Heating with a gauge length of 25mm and a maximum strain 10%. A thermal couple was in contact with the middle of the heated part of specimen to measure its actual temperature. The whole testing system was covered by aluminium foil to reduce convection and stabilize the temperature in the furnace, as shown in Figure 1.


(a) MTS 810 Material Testing System (b) MTS 632.54F-11 Axial Extensometer

Figure 1. Test equipment for tensile test of prestressing wire in and after fire

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Test Procedure

Tensile Tests at Elevated Temperatures

The steady state method was employed. Each specimen was heated up to a constant target temperature (i.e. 100℃, 200℃, 300℃, 350℃, 400℃, 500℃, 600℃, 700℃ and 800℃) and maintained for 15 minutes for stabilization with one end gripped and the other end free. Afterwards the free end was gripped and a displacement-controlled loading rate of 2mm/min was applied until the specimen ruptured. The extensometer was detached before rupture of the specimen for protection of the extension rods. The data obtained showed that the strain rate was approximately 0.003/min, which fell in the range of 0.005±0.002/min as specified in the ASTM Standard E 21-09 (2009). The load and strain were recorded continuously by a computer at a sampling frequency of 5Hz.

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Tensile Tests After Cooling

In the test, the specimen was heated up to the target temperature and maintained constant for 15 minutes for stablization with one end gripped and the other end free. Afterwards the furnace was switched off and slightly opened, allowing the specimen to cool down naturally to ambient temperature. When the steel temperature reached the room temperature, i.e. 25℃, the free end was gripped and a displacement-controlled loading rate of 2mm/min was applied until the specimen ruptured. The extensometer was detached before rupture for protection of extension rods.

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RESULTS AND DISCUSSIONS

Determination of mechanical properties

The stress obtained was engineering stress assuming a constant cross sectional area and ignoring the necking effect. The Young's modulus E was taken as the tangent value of initial proportional section of the stress-strain curve. The "yield" strength $f_{0.2\%}$ was taken as the 0.2% proof stress (non-proportional elongation). The ultimate strength f_u was the maximum stress in the stress-strain curve. The reduction factors $(E_T/E, F_{0.2T}/F_{0.2}, F_{uT}/F_u)$ for various quantities were defined by the ratio of the mechanical property at elevated temperature to that at ambient temperature, where the subscript T denotes those at elevated temperature.

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Test results at elevated temperature

The mechanical properties at elevated temperatures shown as curves of reduction factor against temperature are compared to available results as shown in Figure 2. The Young's modulus, the yield strength and the ultimate strength of the prestressing wires have different trends of decline generally starting from 200℃. The Young's modulus of Grade 1860 prestressing wire to GB/T5224 at 400℃, for instance, is 82.9% of that at ambient temperature while the yield strength and ultimate strength are 60.7% and 59.1% of those at room temperature respectively.

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Comparison of Mehcanical Properties with Available Results

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Figure 2(a) shows that most of the reduction factors for Young's modulus from other researchers are conservative at temperatures above 400℃. The reduction factor of Fan and Lü (2002) on Grade 1860 steel is the most conservative for temperatures of 20℃ to 200℃, while that of Wang et al. (2010) is the most conservative for 500℃ to 600℃. The reduction factor for Young's modulus of prestressing steel wire predicted by Zhou et al. (2008) is not conservative for temperatures of 200℃ to 400℃, but is conservative from 500℃ to 700℃.

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Figure 2(b) shows that the reduction factors for yield strength of prestressing wire to GB/T5224 and BS 5896 generally agree with each other except for a relatively large discrepancy at 350℃. The reduction factors for yield strength predicted by BS EN 1992-1-2 (2004) are conservative at temperatures between 200℃ and 500℃, but adequate for temperatures from 500℃ to 800℃. The

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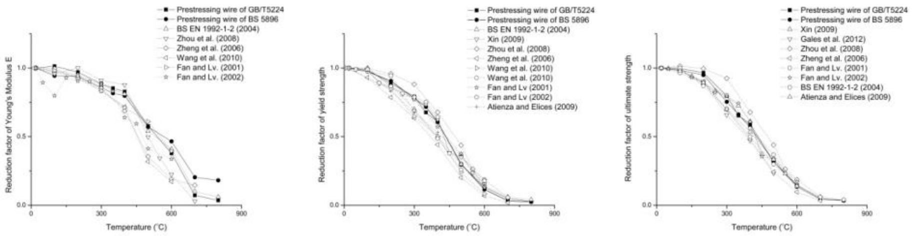
results obtained by Zhou et al. (2008) are not conservative at temperatures from 100℃ to 600℃. The results obtained from Zheng et al. (2006) and Wang et al. (2010) are the most conservative among all.

Figure 2(c) shows less variability of ultimate strength at elevated temperatures compared to that of yield strength. BS EN 1992-1-2 (2004) gives conservative reduction factor for ultimate strength at temperatures from 200℃ to 500℃, but agree relatively well at temperatures of 100℃, and 600℃ to 800℃. For the ultimate strength of prestressing steel wire to GB/T5224 and BS 5896, the reduction factors by Gales et al. (2012) for 100℃ to 500℃ and Zheng et al. (2006) for 100℃ to 700℃ are generally conservative. By comparison, those from Zhou et al. (2008) are not conservative.



(a) Young's modulus (b) Yield strength (c) Ultimate strength

Figure 2. Reduction factors for prestressing steel wire at elevated temperature

Empirical formula for mechanical properties at elevated temperatures

According to the test results, the mechanical properties of prestressing steel wire can be expressed as

$$\xi(T) = \xi_0 \times f(T) \tag{1}$$

where T is the temperature in ℃, $\xi(T)$ is a mechanical property (i.e. Young's modulus E, yield strength, or ultimate strength at temperature T), ξ_0 is the mechanical property at ambient temperature and $f(T)$ is the corresponding mechanical reduction factor at temperature T given by

$$f(T) = k + \frac{1-k}{1+\frac{T}{a}+\left(\frac{T}{b}\right)^2+\left(\frac{T}{c}\right)^8+\left(\frac{T}{d}\right)^{64}} \tag{2}$$

where k, a, b, c and d are parameters determined from experimental data.

The parameters k, a, b, c and d by fitting experimental results of prestressing steel to GB/T5224 and BS5896 are presented in Table 2.

Table 2. Parameters for prestressing steel to GB/5224 and BS 5896

	Steel	k	a	b	c	d
Young's modulus	GB/T5224	-0.0572	7.00E+09	950.37	580.74	100000
	BS 5896	0.0965	7.00E+09	724.35	589.82	100000
Yield strength	GB/T5224	0.0142	7.07E+09	594.12	469.91	100000
	BS 5896	0.0027	7.00E+09	623.26	470.6	100000
Ultimate strength	GB/T5224	0.0257	8.00E+09	602.83	467.09	100000
	BS 5896	0.0159	7.00E+09	564.32	473.03	100000

Test results after cooling

The reduction factors for Young's modulus, yield strength and ultimate strength after cooling are plotted and compared to available results in Figure 3. In general, the Young's modulus of prestressing steel can be fully recovered from exposure to elevated temperature after cooling as shown in Figure 3(a). In comparison with the reduction factor at elevated temperatures, Young's modulus is found to depend on steel temperature and is recoverable after cooling. The Young's modulus as predicted by Fan (2004) for peak temperatures of 800℃ and 900℃ is conservative. The result of Fan and Lü (2002) for Grade 1570 prestressing wire (diameter 5mm) is conservative for temperature above 900℃.

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The variations of yield strength of prestressing steel wire to GB/T5224 and BS 5896 after cooling are quite similar. The results of Fan (2004) are conservative compared to the present results for each peak temperature tested, with 10% reduction of yield strength after cooling from 100℃. The reduction factor of yield strength predicted by Fan (2004) shows a reversed trend for cooling from temperatures above 700℃ while the present results do not show such a trend. This could be caused by subsequential enhancement in strength because of formation of martensite due to rapid cooling from the critical forming temperature 723℃ (Meyers and Chawla 2009). The cooling rate in the present work was slower than that of Fan (2004), thereby preventing formation of martensite. The results provided by Zheng et al. (2006) for Grade 1770 prestressing wire (diameter 5mm) after cooling are conservative for peak temperatures above 200℃.

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Similarly, the results of residual ultimate strength of Fan (2004) are the most conservative for peak temperatures ranging from 400℃ to 700℃, but they are not conservative for peak temperatures between 700℃ and 900℃ with a reversed trend there. Atienza and Elices (2009) provide conservative results for residual ultimate strength for maximum temperature from 300℃ to 600℃, while Zheng et al. (2006) give conservative prediction for ultimate strength for temperatures from 400℃ to 700℃.

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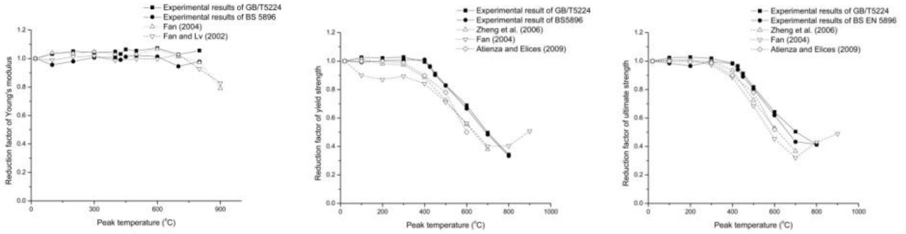

(a) Young's modulus (b) Yield strength (c) Ultimate strength

Figure 3. Reduction factors for prestressing steel wire after cooling

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Empirical formula for mechanical properties after cooling

Based on the test results, the Young's modulus after cooling can be regarded as unchanged, i.e.

$$E_{ac}(T) = E_0 \tag{3}$$

where $E_{ac}(T)$ is the Young's modulus after cooling, T is the peak temperature in ℃ the wire has gone through, and E_o is Young's modulus at ambient temperature.

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For residual strength after cooling, piece-wise linear functions are employed. The reduction factor for residual strength of prestressing steel wire to GB/T5224 is given as

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$$f_{yac}(T) = \begin{cases} 1, & 20℃ < T < 400℃ \\ 1.65469 - 0.00164 \times T, & 400℃ \le T \le 800℃ \end{cases} \tag{4}$$

$$f_{uac}(T) = \begin{cases} 1, & 20℃ < T < 400℃ \\ 1.655 - 1.64 \times 10^{-3} \times T, & 400℃ \le T \le 700℃ \\ 1.142 - 9.175 \times 10^{-4} \times T, & 700℃ < T \le 800℃ \end{cases} \tag{5}$$

where $f_{yac}(T)$ is the reduction factor for yield strength after cooling from the peak temperature T, and $f_{uac}(T)$ is the reduction factor for ultimate strength after cooling.

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Similarly, the reduction factor for residual strength of prestressing steel wire to BS 5896 is given as

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$$f_{yac}(T) = \begin{cases} 1, & 20℃ < T < 400℃ \\ 1.707 - 1.76 \times 10^{-3} \times \mathrm{T}, & 400℃ \le T \le 800℃ \end{cases} \tag{6}$$

$$f_{uac}(T) = \begin{cases} 1, & 20℃ < T < 400℃ \\ 1.71708 - 1.83 \times 10^{-3} \times T, & 400℃ \le T \le 700℃ \\ 0.55074 - 1.684 \times 10^{-4} \times \mathrm{T}, & 700℃ < T \le 800℃ \end{cases} \tag{7}$$

CONCLUSIONS

In the present study, the mechanical properties of prestressing wires from two different sources in and after fire are investigated by sophisticated equipment with the aim of upgrading the reliability and accuracy of the database of material properties at elevated temperatures for performance-based design purposes. The results are compared to available results from research literature and design codes. Empirical formulas are also proposed.

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